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The consequences of leaving vast mined-out areas standing on coal pillars*

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SYNOPSIS

Coal mining has been practised in South Africa for over one hundred years. The total production increased gradually in the early pat of the twentieth century, but over the past twenty years the rate of growth has been considerable. Although opencast mining has contributed largely to this increase in production in recent years, underground bord-and-pillar operations still contribute slightly less than 50 per cent of the total production. The paper highlights problems arising from old bord-and-pillar workings, and an indication is given of how some of the problems have been addressed.

SAMEVATTING

Steenkoolmynbou word al meer as honderd jaar lank in Suid-Afrika beoefen. Die totale produksie het aan die begin van die twintigste eeu geleidelik toegeneem, maar die afgelope twintig jaar was daar 'n beduidende groeitempo. Hoewel dit hoofsaaklik dagmynbou was wat in die jongste tyd tot hierdie toename in produksie bygedra het, dra ondergrondse pilaarmynbou nog net minder as 50 persent van die totale produksie by. Die referaat wys op probleme wat met ou pilaardelfplekke ondervind word en gee 'n aanduiding van hoe sommige van die probleme aangepak is.

Introduction

Coal mining in South Africa started at Molteno in the eastern Cape in the mid-1860s, and about twenty years later, following the discovery of gold on the Witwatersrand, coal mines were established in the regions of Springs and Vereeniging. During the early part of the twentieth century, coal production increased at a rate of about 300 000 tons per year, from a total production of about 3 million tons at the turn of the century to about 12 million tons in 1930. By that time, coal mining in the Transvaal had moved further east of Johannesburg into the areas of Delmas, Witbank, and Middelburg. From the mid-1930s to the mid-1960s, there was an increase in the rate of growth of total coal production (Fig. 1) so that, by 1965, the coal production for the country approached 48 million tons. Therefore, over this 30-year period, the average increase in production was in the region of 1,1 million tons per year. The 20-year period between 1968 and 1988 resulted in a tremendous growth in coal production, with the increase per year averaging about 6,8 million tons over the whole period. This growth led to a total coal output for 1988 of approximately 186 million sales tons.

The tremendous growth in coal production in recent years has been due mainly to the contribution by opencast mines, the production from which is mainly for export purposes. However, although not as dramatic as in the case of opencast mines, there has also been an increase in underground production (Fig. 2). Of the total underground production of 114 million tons in 1988, 30 million tons arose from total extraction operations and 84 million tons from bord-and-pillar workings. Thus, 45 per cent of the total coal produced in 1988 was obtained from bord-and-pillar operations.

Bord-and-Pillar Mining

Bord-and-pillar mining is a method of partial coal extraction that involves leaving a proportion of the coal underground in the form of the pillars to support the overlying strata. This method of coal extraction is not unique to South Africa but is used extensively in the USA, Australia, and India.

The relatively shallow, horizontal, thick coal seams characteristic of most South African coalfields have been extracted economically for many years by the bord-and-pillar method. The conditions of the coal seams, particularly in the Transvaal, favour the bord-and-pillar method, in which a reasonably high percentage extraction of the coal reserves can be obtained from a relatively low capital investment in equipment. Although the system has been used in the thinner and deeper coal seams in Natal for many years, it is only in the last ten to fifteen years that the use of pillar extraction has increased in the thicker and shallower seams in the Transvaal. Pillar extraction, in a manner similar to the longwall method for underground applications and strip mining for opencast or surface applications, is a 'total' extraction method.

During the period from 1900 to 1988, approximately 3400 million sales tons of coal were produced, of which 2600 million sales tons are estimated to have been obtained from the bord-and-pillar method, the remainder being derived from 'total' extraction operations. On the assumption that bord-and-pillar workings achieve an average extraction of 60 per cent, the quantity of coal remaining in the ground as coal pillars is about 1700 million tons. On the further assumption that the average pillar dimension is 10 m by 10 m with a height of 3 m and a density of 1,5 tons per cubic metre, then the number

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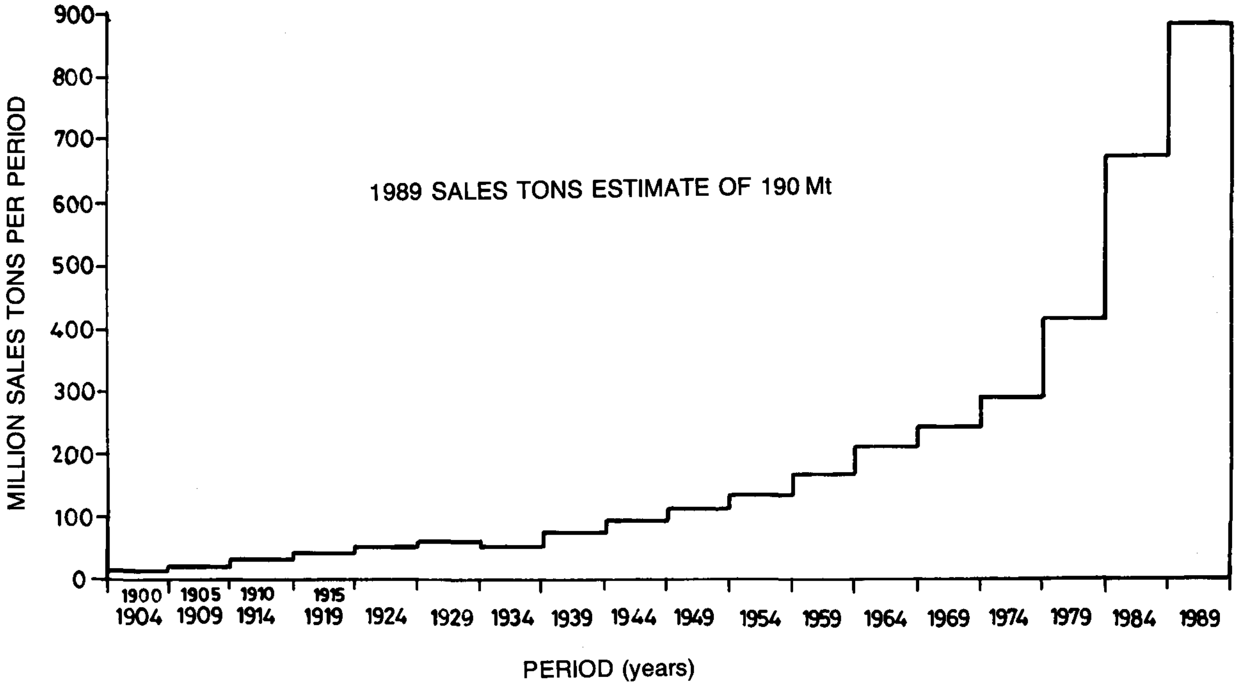


Fig. 1—Rate of growth of total coal production in South Africa

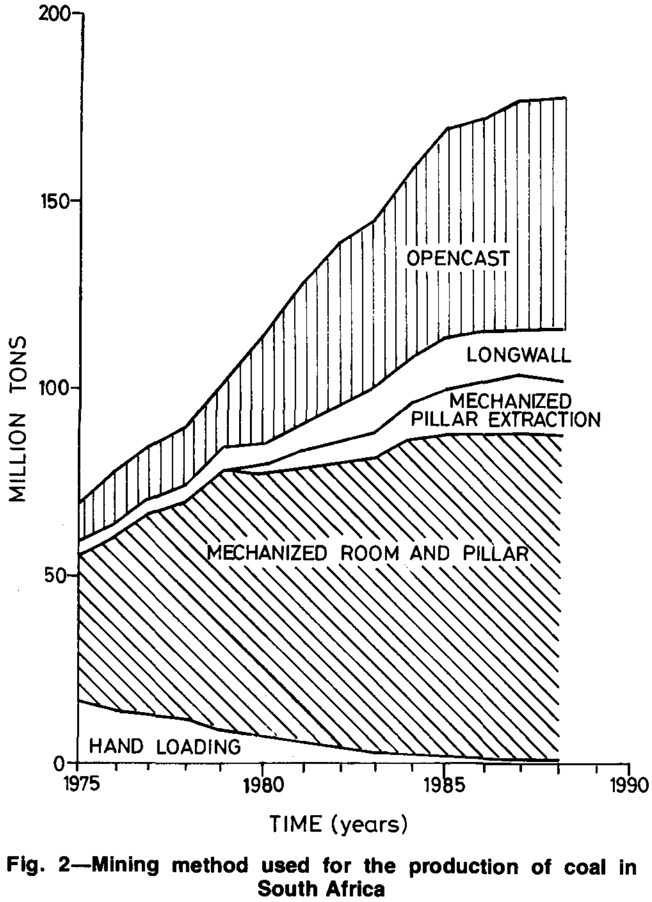


Fig. 2—Mining method used for the production of coal in South Africa

of coal pillars formed this century will be in the region of 4 million. On the additional assumption that the average bord width is 6 m, the area enclosed by one pillar and half the bord width round the pillar is 256 m^2. From the foregoing it can be deduced that the total area occupied by the 4 million pillars is in the region of 1025 million m^2, which is equivalent to a square with a side length of 32 km. Although the estimated area is insigificant compared with the total surface area of the country, the localized nature of the pillar workings does pose local problems.

Of the total coal produced since 1900, one-third was mined prior to 1967 while two-thirds were mined in the succeeding 21 years. Because of the more rapid growth in opencast mining during the latter period, the ratio of bord-and-pillar production between the two periods is slightly different from that applicable to total production. It is estimated that approximately 1100 million tons (or 42 per cent) were derived from bord-and-pillar operations prior to 1967 and 1500 million tons (or 58 per cent) in the remaining 21-year period. If the percentage difference in bord-and-pillar production in the two different periods is applied to the total number of pillars left underground, then 1,7 million of the 4 million pillars were formed prior to 1967 and 2,3 million were formed subsequently.

Pillar Design

In bord-and-pillar mining, coal pillars are left underground to support the overlying strata. If the pillars when mined are too small, there is the danger that they will collapse; on the other hand, if the pillars are too large, coal is left in the ground unnecessarily. South Africa is the only country where the dimensions of the coal pillars are determined according to a specific design formula[1]. It was the unfortunate disaster at Coalbrook Colliery in 1960 that gave rise to the investigations that eventually resulted in the now well-known formula of pillar design. The formula was derived from a statistical analysis of collapsed and stable pillar workings prior to 1966 and, because of its empirical nature, the formula is strictly valid only within the boundaries of the initial data. The pillar-design formula makes use of the safety-factor concept that the strength of the pillar must be greater than the load acting on it. Unlike man-made materials, geological strata are fairly variable in their material properties and are subject to discontinuities that, together, make the calculation of pillar strength imprecise. Therefore, the safety factor recommended for normal bord-and-pillar operations is 1,6 and, in the case of main developments, which have to last the life of the mine, a value of 2,0 is applied. Pillar collapses have occurred since 1967, the date of inauguration of the formula but, as shown by Wagner and Madden[2], the numbers of collapses that occurred between 1967 and 1984 were within the limits of probability of the design procedure.

Problems Associated with Old Pillar Workings

Since 1967, bord-and-pillar workings have been designed according to specific guidelines[3]. Prior to 1967, the dimensions of such workings were based mainly on local experience and, although the workings were stable at the time of mining, the long-term effects on pillar (or bord) stability were not always considered or appreciated. Many of the current problems associated with bord-and-pillar workings arise from workings mined more than 20 to 25 years ago.

Some of the problems from old pillar workings depend on the depth of the workings, while others are independent of depth. The former are related to rock-engineering aspects of the workings and overlying strata, while the latter are concerned mainly with the underground environmental conditions. The rock-engineering factors usually impact on a much wider community because the problems normally affect the surface. In the eyes of the general community, the problems that result in surface effects assume far more importance than those underground. In this respect, it is considered that burning shallow coal seams are due to a rock-engineering problem rather than to an underground environmental problem.

Although old bord-and-pillar workings are often associated with problems, they also have their uses, particularly for storage in the vast volumes of space surrounding the support pillars. The practical and economic use of old bord-and-pillar workings is an aspect that, perhaps, would merit further exploration.

Rock-engineering Considerations

The two main rock-engineering considerations are the collapse of pillars over a large area, resulting in a subsidence basin on surface, and the collapse of underground roadways that extend to surface, which results in a sink-hole or chimney. The collapse of pillars has been extensively covered by Madden[4] and MacCourt *et al.*[5], particularly in regard to the influence of mining dimensions and the magnitude of the resulting subsidence basin.

As the knowledge of pillar-design procedures has improved with time and the procedures have been applied in practice, so the incidence of major pillar collapses has decreased. Of seventeen pillar collapses that occurred between 1966 and 1988, documented and assessed by Madden[4], only three occurred in bord-and-pillar panels that had actually been mined during that period. The remaining fourteen had all been mined prior to 1966 before the design procedures had been implemented.

The unpredictable and uncontrolled subsidence resulting from the collapse of old bord-and-pillar workings can be far more damaging than that resulting from total extraction panels. In the latter case, caving or the collapse of the overlying strata is planned, and the magnitude and extent of the resulting subsidence can be predicted within acceptable limits. The ability to predict the ground movements in such circumstances is particularly beneficial where total extraction panels are planned to undermine surface structures.

In old bord-and-pillar workings, the majority of which are inaccessible for inspection underground, there is no definitive means of determining whether or when failure will occur. The application of the pillar-design formula referred to previously, using dimensions obtained from old plans, will indicate the safety factor of old workings. The lower the safety factor below the value of 1,6, the greater the chance of collapse but, as indicated by Madden[4], other factors such as the width-to-height ratio of the pillar, the size of the pillar, and the areal percentage extraction also have an influence. Thus, in the case of shallow bord-and-pillar workings at depths less than 40 m, the safety factor is not the main parameter that determines potential pillar collapse, but a number of other factors have also to be considered. The fact that the actual mining dimensions could be considerably different from the dimensions shown on old plans is a further complicating factor.

When the thickness of the overlying strata above pillar workings is less than 20 to 25 m, roof failure in the underground roadways, particularly at intersections, often extends to surface in the form of sink-holes. The geological characteristics of the overlying strata and the mining dimensions determine the upward extent of a roadway or intersection roof collapse. For a roadway roof collapse, the height of caving into the upper strata is less than for a collapse of an intersection in similar mining and geological conditions. In addition, the wider spans created at intersections induce higher tensile and shear forces into the roof beam, thereby creating conditions more likely to lead to roof failure. Although highly competent strata, such as massive sandstone and dolerite sills, prevent the upward migration of roof collapses, the closer these are to surface, the greater the chances that they have been weakened by weathering. Thus, weathered strata will be just as susceptible to failure as weak, highly laminated, carbonaceous shale strata. The height of caving can be estimated by considering the size of the excavated space and determining the thickness of solid strata that is required to fill the space, taking cognizance of the strata's bulking characteristics. When the caved strata completely fill the excavation and have bulked sufficiently to provide support to the sides of the cavity, further collapse is prevented, and the upward migration of the collapse is arrested. It is apparent that, in such circumstances, there will be no surface disturbance nor cause for concern to surface owners or users.

In England, Whittaker and Reddish[6] investigated the occurrence of sink-holes resulting from bord-and-pillar (or room-and-pillar) workings in stratified ironstone. The diameter of the sink-holes investigated was found to be within the range B to $B\sqrt{2}$, where B is the bord or room width and $B\sqrt{2}$ is equivalent to the diagonal across an intersection. Fig. 3 illustrates the height to which caving

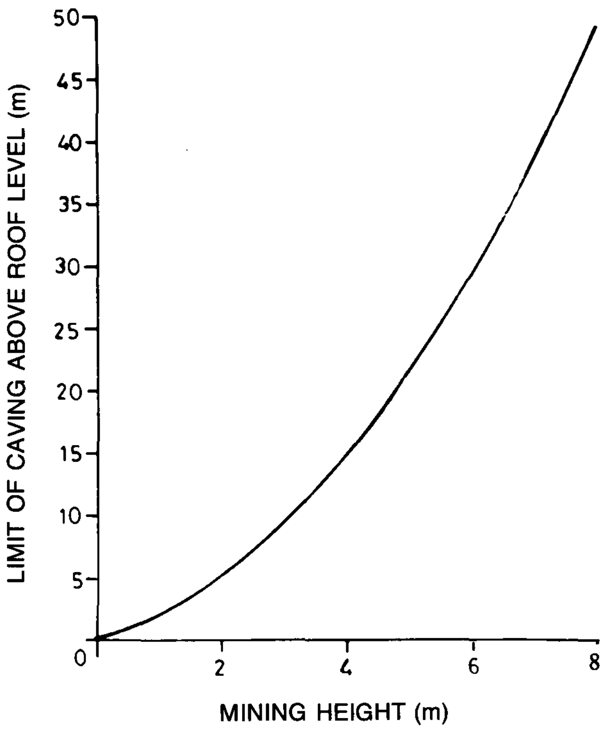
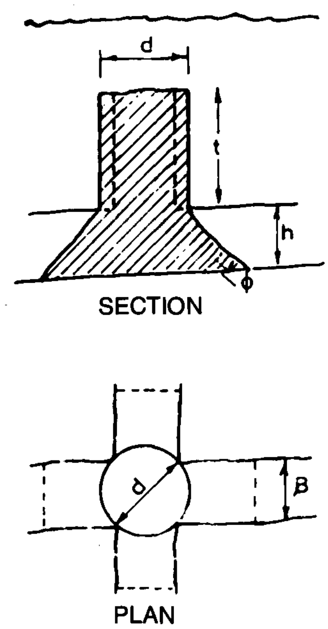


Fig. 3—Extent of caving above roof level for different thicknesses of extracted seam



$$t = \frac{4}{(k-1)} \pi d^2 [2h^2 \cot \phi + h \beta^2]$$

WHERE
k = BULKING FACTOR (1,5)
d = DIAMETER OF SINK HOLES ($\beta\sqrt{2}$) m
h = HEIGHT OF EXTRACTION, m
ϕ = ANGLE OF REPOSE (35°)
β = BORD WIDTH, m

extends in the roof for different extracted-seam thicknesses, after which further collapse will not take place because of the effect of the bulking. The assumptions made are as indicated on Fig. 3.

If the thickness of the overlying stratum is less than the limit height of caving, a sink-hole will apear on surface to the depth indicated in Fig. 4, which shows that, for different extraction heights, the depth of a sink-hole increases as the thickness of the overlying strata decreases. As the thickness of the overlying strata decreases, a position is reached in which the broken material from the collapse is only sufficient to fill the space in the underground intersection up to the height of normal roof level. At this stage, or even earlier if coal has been left in the roof, the coal seam is exposed to the external environment.

From the foregoing, it is not unexpected that, where bord-and-pillar workings have been mined to a height of about 6 m at depths of cover in the region of 10 to 15 m, the collapse of an underground intersection resulted in the formation of a sink-hole. Even if the coal seam was not exposed at the time of the initial collapse, this can occur with time owing to the effect of water washing the caved material into the old workings. From the point of view of land usage, it is important that the locations of these workings in shallow coal seams should be known accurately.

One of the greatest problems associated with the collapse of shallow workings is the onset of spontaneous combustion.

The Underground Environment

Old bord-and-pillar workings are either sealed-off from the rest of the underground workings, or are ventilated by allowing small quantities of air to 'bleed' through them. Each method has its advantages and disadvantages, but this is a subject considered to be outside the scope of this paper. The main consideration is to ensure that explosive mixtures of gases are not allowed in these areas. The experience gained in various collieries or mining regions often dictates the method to be adopted in the treatment of old workings. Some mines have more methane than others, while others may experience problems with spontaneous combustion. However, it is important that old areas are monitored in order to detect and control, if necessary, any adverse changes that may take place. The cost of control and prevention is often far less than that of a fire or explosion in old workings, particularly if such an incident can endanger current operations. The above environmental aspects can be considered to be confined to a specific mine, particularly at depths in excess of say 40 m, and any dangerous situation would also be limited to that mine.

Burning Shallow Coal Seams

Although burning shallow coal seams represent an obvious environmental hazard, as was mentioned previously it is considered that one of their main causes is the collapse of underground roadways or intersections associated with shallow bord-and-pillar workings. Such collapses expose the coal seam, or in some cases carbonaceous shale, which can eventually ignite when oxidation takes place. All burning shallow coal seams may not start from a sink-hole, but may start where old bord-and-pillar workings are exposed in the highwall of an opencast

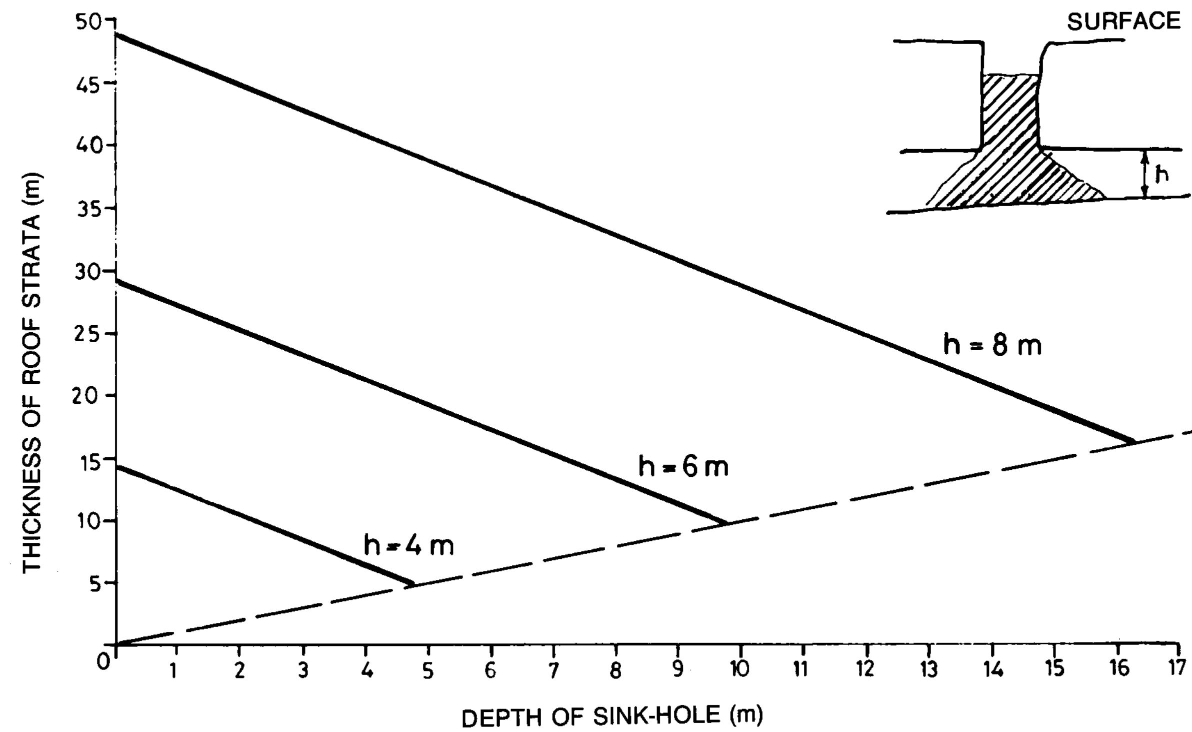


Fig. 4—Depths of sink-hole for different extraction heights

operation, or may result from roof fractures in shallow workings extending through to surface without a collapse having taken place. All coals will ignite spontaneously given the right conditions for that particular coal, although some coals ignite more easily than others. Researchers have for many years investigated the characteristics of coal to determine their influence on a coal's susceptibility to spontaneous combustion. However, irrespective of the coal characteristics, if the atmosphere surrounding the coal is not conducive to combustion, ignition will not take place.

Where shallow, previously sealed coal workings become partially ventilated as a result of the ingress of air through surface cracks or the partial collapse of workings, conditions conducive to self-ignition are created. Where the workings are many years old, the sides of the coal pillars will be highly fractured due to weathering and fine coal will be lying in the roadways. Thus, a large surface area of coal is available for oxidation and, with the existence of only a limited amount of air, the exothermic reaction will create a rise in temperature that will eventually become self-generating. If such occurrences are not detected early and controlled adequately, large areas of coal can be destroyed and surface areas seriously affected. The surface environmental effects can have an impact on a wide selection of the general population, with a corresponding detrimental effect on the image of the coal industry.

The three most common methods of dealing with burning shallow coal seams are to seal the site to prevent the ingress of air, to dig out the burning coal, and to trench round the burning area to contain it within a specific boundary. The choice of method depends on the individual circumstances and the extent to which the heating or burning has progressed. Whichever method is used, the outer limits of the affected area should first be established, and use can be made of a method of temperature monitoring in conjunction with isothermal plotting as described by Sullivan[7]. If the limits of a heating are not fully determined, much time and money will be wasted on a control method that may not achieve the required objective, namely the containment and eventual extinction of the heating. Temperature monitoring from surface boreholes combined with isothermal plotting has been used successfully to identify heatings in a shallow underground bord-and-pillar section at a mine in the Witbank area.

To ascertain the airflow patterns within the old workings, tracer-gas studies using sulphur hexafluoride were also undertaken[7]. The use of tracer-gas techniques in this particular case assisted in showing the paths of air ingress, which could then be sealed to starve the area of air.

Conclusions

The underground environmental problems associated with old bord-and-pillar workings can result in catastrophic incidents. However, because these incidents generally affect only one mine, they tend not to have the same impact on the image of the coal industry in the eyes of the general population as do mining incidents that affect the surface.

Much knowledge has been gained over the past 20 to 25 years with regard to the design and performance of coal pillars, and the adoption by the coal industry in 1967 of design procedures has been beneficial in reducing rock-engineering problems that impact on the surface.

Many of the present-day surface problems associated with shallow bord-and-pillar workings result from operations mined many years ago. With regard to fires and heatings in shallow bord-and-pillar workings, the methods now used help operators to locate the source and extent of an incident more accurately so that they can apply control procedures in a more cost-effective manner.

Acknowledgements

Investigations into the design of bord-and-pillar workings and burning shallow coal seams form part of the coal research programme of the Chamber of Mines Research Organization. Both areas of research have received financial assistance under the auspices of the Strata Control Advisory Committee and the Explosion Hazards Advisory Committee of the Coal Mining Research Controlling Committee.

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IFAC news*

During the 11th World Congress held by the International Federation of Automatic Control (IFAC) in Tallinn, Estonia, USSR, from 13th to 17th August this year, Dr J.D.N. van Wyk of South Africa was elected a Council Member of that body.

IFAC, which was founded in 1957, promotes the science and technology of control in the broadest sense in all systems in both theory and application, whether they relate to engineering, physical, biological, social, or economic fields. It is also concerned with the impact of control technology on society.

IFAC consists of 47 National Member Organizations (NMOs) representing countries worldwide. The General Assembly, comprising representatives from each NMO, is the final decision-making body in IFAC. It meets every three years to elect a President and other office bearers, as well as a Council. This Council is the governing body of the affairs of IFAC for each triennium. The South African Council for Automation and Computation (SACAC) is the South African NMO to IFAC.

The present President is Professor Brian Anderson of Australia, and the Council consists of 9 members. The other 8 members come from West Germany, Great Britain, Belgium, Canada, Japan, Czechoslovakia, Denmark, and France.

Dr Van Wyk has been active in IFAC over a number of years in positions such as Chairman of the Technical Committee on Computers, as Vice-Chairman of the Technical Board and, during the past three years, as Chairman of its Policy Committee. He received one of IFAC's outstanding service awards during the Congress in Tallinn. This award is given for 'sustained outstanding performance in major leadership positions in IFAC'.

Dr Van Wyk retired as Chief Director of the National Electrical Engineering Research Institute of the CSIR in 1988. He is at present associated with the Foundation for Research Development of the CSIR as far as his IFAC activities are concerned.

Many symposia, both local and international, have been hosted by SACAC, including IFAC events on topics such as power generation, mining, minerals and metallurgy, and software for computer control. It is significant that SACAC, with IFAC, has maintained these valuable international links in spite of sanctions and negative pressures from many quarters.

At present Mr Günter Sommer of Mintek is a Vice-Chairman of the Applications Committee, responsible for IFAC's activities in mining, and mineral and metal processing.

SACAC has a proud record of involvement by South Africans on several IFAC technical committees and now Council, the executive steering body of IFAC.

IFAC arranges some 30 technical events annually worldwide under the auspices of its 14 technical committees, each responsible for a specialist field in control.

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Corrigendum

The foundation date of the Western Cape Branch of the SAIMM was incorrectly given as November 1989 in the 'Spotlight on the SAIMM branches', which was published in the June issue of this *Journal* (vol. 90, no. 6, p. 149).

The Western Cape Branch was, in fact, founded on 13th November, 1986. As pointed out in a letter from Professor F.L.D. Cloete of the University of Stellenbosch, who drew our attention to the error, the Western Cape Branch is the second oldest of the SAIMM branches, the OFS Branch being the oldest.