CONTROL STRATEGIES FOR COAL DUST AND METHANE EXPLOSIONS IN UNDERGROUND COAL MINES: SOUTH AFRICAN RESEARCH AND DEVELOPMENT INITIATIVES

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SUMMARY

Research and development conducted by CSIR - Mining Technology in the areas of active continuous miner based coal dust/ methane explosion suppression systems, passive 'bag based' stone dust barriers systems, design and positioning of refuge bays, integrated escape and rescue strategies, and neural network based coal dust/methane explosion risk assessment is briefly described.
It is concluded that effective catastrophic risk management of coal dust/methane explosions is dependent on an integrated, systems approach that encompasses fundamental understanding of hazard sources, qualitative and quantitative probability of occurrence, magnitude of consequences and efficacy of control and recovery measures.

INTRODUCTION

Catastrophic coal dust and methane explosions are an unacceptable, but real consequence of underground coal mining operations. Conventional hazard amelioration, typically, involves a strategy of risk management based on a reduction of event probability through proactive hazard awareness and control processes. Central to this approach is a focus on explosion mechanisms and controls necessary to prevent their occurrence and to minimize associated consequences.
Formal research into coal dust and methane explosion control strategies has been ongoing in South Africa for the last decade with significant recent advances in the understanding of explosion mechanisms and the development of control systems. Most of this work has been conducted by CSIR - Mining Technology, the mining research division of CSIR South Africa; this paper briefly reviews recent research and development conducted by the organization .

AN OVERVIEW OF THE SOUTH AFRICAN COAL MINING INDUSTRY (1) (2)

South Africa is the fourth largest black coal producer in the world and the second largest exporter after Australia. In 1995 some 256,7 million run of mine tons were produced, up from 243,1 million tons the previous year. Total sales amounted to R12,8bn (±A$3,8bn) of which exports accounted for R6,5bn (±A$2,0bn) in foreign exchange. The coal industry is a vital cog in the South African economy in terms of employment, foreign earnings, power supply, fuel, chemical by products, heating, industrial manufacturing and supply industries. Total employment in the industry is ± 61 000 with each wage earner supporting an estimated 'extended family' of seven.
During 1995 approximately 53% of production came from underground workings. Underground mining methods comprised bord and pillar using continuous miners/road headers (33,5% or 69,3mt), drill and blast bord and pillar (12,3% or 25,3mt), longwall (4,2% or 8,7mt), shortwall (1,3% or 2,6mt)and longwall/shortwall development (2,3% or 4,7mt). Surface mining using draglines (34,2% or 70,7mt) and truck and shovel methods (12,3% or 25,3mt) accounted for the remainder of production. Forty-four percent of production comes from three mines producing more than one million tons per month. Productivity in terms of tons/man/year has increased from approximately 1800 in 1990, to 3300 in 1995.

COAL INDUSTRY SAFETY TRENDS (3)

Although fatality and reportable injury rates (per 1 000 employed) show a marked downward trend from 1,54 and 51,5 respectively in 1950 to 0,4 and 4,2 respectively in 1995, this trend is marred by the incidence of disasters in which large numbers of lives are lost. These disasters are usually associated with methane or coal dust/methane explosions.
A key driver of change in the South African minerals industry has been the promulgation of the Mine Health and Safety Act (29/1996). The Act arose from the findings of the Leon Commission of enquiry into health and safety and as a result South

Africa has entered a period of renewed social responsibility towards workforce safety and health. The Leon Commission [4] identified four main areas of concern:

- falls of ground (including rock bursts),
- accidents in underground haulage and transportation systems,
- the incidence of occupational ill-health among miners, and
- the continuing incidence of disasters from fires and coal dust in coal mines.

These aspects of mine health and safety performance, although specifically identified within the context of the South African minerals industry, can be seen to be fairly generic to the global mining industry.

Similarly several key concepts can be identified as being central to the Mine Health and Safety Act [5] :

- Health and safety are the joint responsibility of the employer, employee and the State.
- Employers and employees are required to identify hazards and minimize related risks.
- Equipment manufacturers, suppliers and maintainers are responsible for the supply of 'fit for purpose' equipment.
- Routine measurement of hazard exposure is crucial to the management of health and safety.
- Health and safety training is essential to be able to assume responsibility for the identification and minimization of risks.

These concepts embody the principles of co-responsibility and elements of self regulation within a framework determined largely by workplace risk assessment and management without which explosion hazard control strategies are meaningless.

CSIR - MINING TECHNOLOGY[6]

The CSIR, with nine operational divisions ranging from aeronautical engineering to transport technology, and employing over 3 000 people, is the largest community and industry directed scientific and technological research and development organisation in Africa. Its Mining Technology division works in close collaboration and strategic partnership with the mining industry, employee organisations and government institutions in acquiring, developing and transferring technologies to improve the safety and health of employees, and to improve the profitability of the mining industry and contribute to the long term wealth and well being of the region.

CSIR - Mining Technology, is structured into three research programmes: Rock Engineering, Mining Systems, and Environmental Safety and Health, which mirror industry concerns in the areas of safety, productivity and health respectively. The recent demise of state funded mining R&D institutions around the world has emphasised the importance of conducting R&D on sound business principles. CSIR - Mining Technology derives 80% of income from contract R&D activities with individual research programmes conducting regular market needs analyses and developing business strategies in response to anticipated five and ten year scenarios.

The Environmental Safety and Health Programme(ES&H) provides multi-disciplinary research, development and technology transfer expertise in the solution of environmental problems, with specialists in a wide range of fields from human physiology and occupational hygiene to pollutant control, mine fires and explosions, ventilation, cooling and escape and rescue strategies. The ES&H programme comprises four functional thrust areas: Occupational Hygiene Services; Environmental Engineering; Coal, Fires, Dust & Explosions and Surface Environment. Activities across thrust areas are consolidated at programme level to ensure an integrated environmental safety and health offering.

COAL DUST AND METHANE EXPLOSION AMELIORATION RESEARCH STRATEGY

Coal dust and methane explosion research and development is conducted in the Coal, Fires, Dust and Explosions research thrust area. Activities are centred at the Kloppersbos explosion research facility approximately 110km north of Johannesburg. The facility was established in 1987 primarily to determine the explosibility of South African coals. Since then the facility has been expanded to include:

- the 200 m mild steel Badenhorst tunnel of 2,5 m diameter used primarily for explosion and barrier evaluation
- a 20 m tunnel, 7 m wide with variable height to 6 m, to simulate roadway face explosions and evaluate machine mounted active suppression systems
- a rectangular test tunnel, 6 m wide x 3,5 m high x 140 m long arranged in a last through road, heading and pillar split configuration, to allow full scale modelling of ventilation

systems under varying dust and methane a 10 m tunnel of 2 m diameter used for limited ignition suppression system testing and demonstration purposes

- a 40 litre explosion vessel for the characterization of coal dusts both with and without methane
- sophisticated laboratory equipment for thermal and gas analysis
- data collection, transmission and analysis equipment
- electronic and mechanical workshops.

Activities are directed towards the development of technology (products, processes, knowledge and skills) to reduce the incidence of catastrophic risk events in the coal mining industry, and typically occur in four areas:

- knowledge generation through industry based research and development activities,
- creation of appropriate laboratory service capabilities,
- training in health and safety skills and awareness, and
- application of specialist knowledge through consultancy services.

Critical technologies that are anticipated to have a significant effect on coal industry safety, in the area of catastrophic risk are, active machine mounted coal dust/ methane explosion suppression systems, passive 'bag based' stone dust barriers systems, integrated escape and rescue strategies, and neural network based coal dust/methane explosion risk assessment. Current developments in each of these areas is considered in turn.

Active machine mounted (continuous miner / road header) coal dust/ methane explosion suppression systems

Most of the coal mined in underground sections in South Africa is extracted using continuous miners. Owing to the incidence of pyrite and sandstone lenses and the regular occurrence of sandstone roof, great potential exists for frictional ignition of methane. In addition to face and cutter head ventilation strategies, the use of water sprays and the evaluation of 'wet head' cutter drums, effort has been directed toward the use of active on-board explosion suppression systems. These systems are mounted on board continuous mining machines and detect the presence of a methane ignition by means of light sensors. The electronic signal from the sensors is used to trigger the suppression system, creating a barrier of flame suppressing material, thus containing the flame in the immediate vicinity of the ignition and so preventing further development and the propagation of a coal dust/methane explosion.

Although commercial systems are widely applied in Europe, differences in mining geometry and practice between South African and European collieries prompted the definition of a South African test protocol, adapted for local conditions from established German protocols, and development of the 20 m rectangular test tunnel at Kloppersbos. Following construction and equipping of the test tunnel, and under the auspices of a SIMRAC (Safety in Mines Research Advisory Committee) project two system tests were devised and conducted on two available systems; a protocol test and a system evaluation test. The objective of the protocol test is to determine if a system or configuration is able to fulfill the following acceptance criteria for various cutter head positions, methane concentrations and roadway widths:

- flame propagation must not reach the operator's position
- pressure shock at the operator's position must be within acceptable tolerance levels
- temperature rise at the operator's position should be less than 100°C over 2 milliseconds
- no false triggering may occur as a result of other equipment in use in underground operations
- equipment downtime associated with a discharge must be less than eight hours

Evaluation testing is concerned with the performance of the system and individual components and primarily centres around risk aspects of engineering 'reliability'.

A large number of tests has been conducted at various methane concentrations ranging from 7,5% to 12%, with and without equipment and the second pass shoulder in the tunnel. The implication of multiple pass mining is that when the second cut is taken, there is a substantial volume of methane immediately adjacent to the continuous miner which must be shielded from possible ignition.

Indications are that active machine mounted explosion suppression systems are a viable means of explosion control. Key aspects are sensor systems, nozzle orientation and the need to extinguish the ignition as rapidly as possible.

Passive 'bag based' stone dust barriers systems

Traditionally the last line of defence against methane or coal dust / methane explosions has been the stone dust or water barrier system. Although the 'Polish' type barrier has Inspectorate approval and is widely implemented in the South African coal industry, some doubts were raised about its

effectiveness following investigations into several ignitions. These doubts, coupled with the fact that erection and maintenance of the system is labour intensive and increasingly costly, resulted in efforts being directed into the development of an alternative passive stone dust barrier system.
The new stone dust bag system in various configurations makes use of a previous concept of containing stone dust in a bag but incorporates a new method of rupturing the bag based on materials properties, relative volumes and a patented suspension device. Evaluation tests have been conducted over a period of two years to establish design and materials specifications, and installation configurations. Two installation configurations, namely, dispersed and concentrated have been devised, with associated stone dust loadings and system spacings. Tests at Kloppersbos and the underground test facility at DMT - Tremonia have indicated that a minimum dynamic pressure of 3 kPa is required for bag rupture and that coal dust / methane explosions are effectively stopped with a stone dust loading of 100 kg/m^2 cross sectional area.

Integrated escape and rescue strategies

Owing to the high concentrations of carbon monoxide, escape in the irrespirable atmosphere that results from an underground explosion or fire is dependent on the use of artificial breathing apparatus. Self-contained self rescuers (SCSRs) thus form the basis of any escape and rescue strategy. SCSRs although being the core technology are largely ineffective unless integrated into an overall escape and rescue strategy comprising components of escape routes, guidance systems, refuge bays, hazard identification and communication systems.
Body worn SCSRs were first introduced into the South African mining industry in the late 1980's, following the Kinross disaster, as a proven but novel means of providing protection to mineworkers in the event of a fire or explosion. A considerable amount of research was required to address various issues associated with their introduction. Aspects covered were:

- the formulation of appropriate rejection criteria for the selection of SCSRs, these centred around the determination of physiological limits for the inhalation of carbon dioxide, definition of breathing resistance limits and establishment of unacceptable inhalation air temperatures
- the development of a non-destructive leak testing procedure to assess the functional integrity of the SCSRs in daily deployment in the industry
- the development of performance evaluation protocols utilizing breathing simulator testing as well as person tests in the laboratory and in underground trials
- compilation of guidelines to assist mines with the implementation of SCSRs, including training programmes and record keeping systems
- the introduction of an ongoing national monitoring system to assess the functional performance of SCSRs deployed within the industry with the objective of determining long term performance trends.

However the primary means of escape is through well maintained, properly designed escape routes. Apart from inherent technology features, the performance of SCSRs is determined by a variety of factors including the physiological characteristics of the wearer and the nature of the escape route. In this regard studies have been conducted to determine the effect of inclination, reduced roof height and zero visibilty on the speed at which escape routes can be negotiated as well as safe travelling distances. It was ascertained that, typically, safe escape distances are reduced from 1500 m, based on a breathing duration criterion, to a maximum of 750 m, when adverse condition criteria are applied. This information is currently used by mines to determine the location of back-up facilities and refuge bays. Current techniques involve the use of long duration SCSR caches and the use of an intermediate breathing station under developent by CSIR - Mining Technology. The mobile air rescue station (MARS) is an easy to operate mobile life support system for underground workers, developed in conjunction with MSA-South Africa. Other initiatives have been directed into SCSR ergonomics and the development of noseclip design to cater for the low ridge noses typical of the majority of the South African workforce. Current R&D initiatives are directed towards improved guidance systems which integrate electronic location devices, gas detection and monitoring systems, and communication systems.

Design and positioning of refuge bays

Refuge bays are an integral part of escape and rescue strategies and are a regulated requirement in South African collieries. The main purpose of refuge bays is to keep workers safe from the effects of poisonous gases and fumes following a fire and/or explosion, prior to rescue initiatives. Whilst refuge bays are not intended to protect workers from an explosion they should have sufficient structural integrity to remain intact following an event so as to provide protection to any surviving workers. Given that the greater the strength of the explosion, the lower the likelihood of any worker surviving, the practical strength requirement for refuge bays should not be significantly higher than the pressure at which the probability of workers surviving and using the refuge bay is fairly good. Coupled with this is the fundamental requirement that a refuge bay should at least prevent the ingress of gases and fumes following an explosion. Within this rationale, considerable effort has been directed into defining the overall strength and viability of rescue bays in the event of fires and explosions. Current refuge bay designs are more than adequate in the event of fire, however it is doubtful that the strength of structures, as defined in various mines' codes of practice, could withstand the force of an explosion. Based on probability of human survival at various explosion over pressures, investigations have revealed that a criterion of 140 kPa should be applied in the design of refuge bay bulkheads.

Of considerable importance are the practical considerations of refuge bay placement and construction. In deciding refuge bay placement the first criterion is that it should be within practicable reach of the workers that it serves. Based on evaluation of SCSR performance under zero visibility conditions, refuge bays should not be further than 750 m from the workplace. This implies, dependent on seam height, that refuge bays would need to be constructed at intervals of between 36 shifts (0,75 m seam height) and about 185 shifts (5 m seam height). Given the robust nature of the construction required for structural integrity of a refuge bay at distances less than 750 m from an explosion, construction of permanent refuge bays at these intervals is impractical. The development of the MARS system, previously mentioned, resulted from the need to create an economic, intermediate staging point and breathing station at distances of less than 750 m from the workplace, that would readily integrate with existing refuge bay designs and positioning.

In the context of fires, aspects investigated include the build-up of heat and carbon monoxide when occupied. Results to date indicate that, without ventilation and an outside carbon monoxide level of 1,5%, carbon monoxide levels in a refuge bay could reach the threshold limit value within 8,5 hours due to contamination from door openings and leakages. Creation of positive pressure inside the bay is therefore critical. Various systems for oxygen generation and carbon monoxide scrubbing are under development by commercial organizations in South Africa.

Neural network based coal dust/methane explosion risk assessment

Exploratory research has been initiated in the area of artificial intelligence and neural networks in an attempt to develop a real time explosion risk assessment and management tool. The approach is based on the concept that changes in, and the rate of change of, certain critical criteria can indicate the possibility of increased risk. In this approach the probability of an ignition rather than an explosion is determined; when this probability exceeds a control value an emergency response is initiated. Current activities are focussed on the identification of critical factors such as diurnal pressure change, methane release rates and seam characteristics, the inter-relationship of factors, their influence on the explosion hazard, and electronics hardware requirements. At a later stage it is anticipated that other factors such as increased production rates, shift duration and cycling, and life style factors which may be linked to human error and negligence would be incorporated. In due course the artificial intelligence system would be integrated with real time hazard monitoring, personnel location and emergency communication systems.

CONCLUSIONS

The research and development initiatives described in this paper are component parts of an overall control strategy for coal dust and methane explosions in South African coal mines. Although described as individual technologies, the potential success of their application lies in a fundamental understanding of explosion hazards and the interaction of people, processes and equipment that comprise mining operations.

The critical learning that has been achieved during this research and development process has not been around the individual technologies but in the understanding that effective risk management and mitigation is dependent on addressing explosion risk from a systems perspective. The development of individual technologies will provide short term improvements in safety performance but longer term significant reductions in catastrophic risk events is dependent on understanding the interaction of mining system components. This approach means:

- recognizing that problems arise from the interaction of the different parts within the system
- integrating and synthesizing diverse components to understand the whole

- focussing on the underlying structure of inter-relationships and inter-actions when devising solutions
- recognizing actions to alleviate a specific problem can result in unintended and undesirable consequences elsewhere in the system
- understanding that the relationship of cause and effect is often obscure
- acknowledging that systems are most effectively changed at 'leverage' points.

The exploratory research into neural networks and explosion risk assessment represents an attempt to develop a systemic understanding that will allow identification of system 'leverage' points - those critical issues where small changes bring about massive benefits. Active and passive barrier systems, escape and rescue strategies, and refuge bay designs are reactive mitigation activities that will save lives in the short term but will not reduce the incidence of methane and coal dust explosions.

Effective catastrophic risk management in the area of coal dust and methane explosions is thus dependent on an integrated, systems approach that encompasses fundamental understanding of hazard sources, qualitative and quantitative probability of occurrence, magnitude of consequences and efficacy of control and recovery measures.

REFERENCES

1) Chamber of Mines of South Africa, Statistical Tables 1995, Johannesburg, South Africa, 1995.
2) South African Institute of Mining and Metallurgy, Colloquium - Coal Mining 2000 and Beyond, Johannesburg, South Africa, 1996.
3) Department of Mineral and Energy Affairs, Safety in Mines Research Advisory Committee - Annual Report 1995, Pretoria, South Africa, 1996.
4) CSIR - Mining Technology, Leon Commission transcripts - internal documentation.
5) Mine Health and Safety Act No. 29/1996, Lex Patria Publishers, Doornfontein, South Africa, 1996.
6) CSIR - Mining Technology, CSIR: Mining Technology Annual Review 1996/97, Johannesburg, South Africa, 1997.