Arc Containment in Underground Flameproof Enclosures

K. Byers, Safety in Mines Testing and Research Station (SIMTARS)

Attention is drawn to the fact that whilst fault levels and operating voltage levels are increasing in Australian underground coal mines, no account is taken in present safety standards of the effect of internal arcing within flameproof enclosures. Results of overseas research on this topic is reviewed, but it is concluded that there is insufficient evidence available to provide the basis of safe design practices. The authors describe the results of arcing test undertaken on seven certified flameproof enclosures with volumes of 0.07 to 1 cu. metres with test currents of up to 10 kA. The five smaller enclosures all caused failure of flame containment, and organic insulation close to the arc was found to aggravate the effects of arcing. Provisional recommendations are made about minimum sizes of enclosures and requirements for fast-acting protection.

1. Introduction

With the development of large underground coal mines in Australia there is a requirement for larger underground mining equipment than has been used previously. For example maximum ratings of shearers, face conveyers, and continuous miners in Australian underground mines were 1050 kW, 750 kW and 420 kW respectively in 1990, compared with ratings of similar machines in 1970 of 200 kW, 200 kW, and 70 kW respectively. This increase in machine ratings has been matched by higher-capacity mine reticulation systems. Face reticulation system operating line voltages of 3.3 kV are becoming common, and there is increasing pressure for these reticulation systems operating at 6.6 kV or even 11 kV .

One of the consequences of using higher capacity electrical supplies is that the current supplied to an electrical fault is higher than in lower capacity systems. Birtwhistle & Byers (1990) on the basis of studies of three-phase fault levels in several large Australian underground coal mines have estimated that maximum fault currents in hazardous areas were 17 kA, 7.2 kA, and 6.9 kA for 1.1 kV, 3.3 kV, and 6.6 kV systems respectively. On the basis of historical trends in equipment ratings it was further estimated that by the year 2000 fault currents may be 24 kA, 11.5 kA, and 11.1 kA for 1.1 kV, 3.3 kV, and 6.6 kV systems respectively.

In hazardous areas of mines high current faults are prevented in trailing cables by individual earthed screens on each phase, and neutral impedance that restricts earth fault currents to 5 A. High current faults can only occur between phases at switching points in the electrical system and switching equipment such as circuit breakers, contactors, and their associated controls are inevitably housed within flameproof enclosures that are constructed and currently tested to Australian Standard 2380-2 (1992).

Flameproof enclosures are designed to prevent the ignition (by, for example, electrical equipment sparking) of an explosive gas mixture within the enclosure, causing ignition of external gas mixtures with subsequent catastrophic damage to the mine. The internal arc is caused by accidental bridging of the phase conductors. The arc is a column of highly-conducting plasma that may have a central temperature of approaching 30,000 K, and dissipate energy as heat, light and sound at the rate of tens of megawatts. It melts metal conductors in contact with it and incinerates organic materials.

Above-ground switchgear assemblies are tested to Australian Standard 1136.1 (1990) in which an internal arcing test is recommended to ensure operator safety. No recognition, however, is given to the possibility of internal arcing faults in flameproof standards. The question, therefore arises as to whether the occurrence of an high power internal arcing fault within a flameproof enclosure could compromise the flameproofness of the enclosure, or could have some other effect that could jeopardise mine or operator safety. The next section of this paper describes work done by previous researchers on the topic of arcing in flameproof enclosures.

2. Previous Work

Previous work has been concerned with the two regimes of low-current and high-current fault arcing. Low current arcing occurs when the arc fault current is limited by series impedance to such a value that circuit breakers do not trip. Arcing and decomposition of dielectrics can continue inside an enclosure over many seconds or even minutes. Decomposition of organic insulating materials may occur and pressure rise is strongly influenced by the type of dielectrics. High current fault arcing causes circuit protection to operate and the arc is quickly interrupted by circuit breakers. Pressure rise in the enclosure is caused by the energy of the arc, but the effect of the high power arc on organic materials does not appear to have been documented.

Low-current Arcing

Lord and Babero (1975) described incidents in Canada and Germany in which bursting of flameproof enclosures appeared to have been accompanied by electric arcing. They showed that tracking across the surface of phenolic insulation inside enclosures, with currents of up to 750 A, caused rapid evolution of volatiles that caused build up of pressure in excess of the design pressure of the enclosure. On the basis of this work the British Coal Board recommended (Luxmore 1976) that arcing resistant insulating materials , and that no material with a comparative tracking index (CTI) less than 250 be used inside flameproof enclosures.

With low current fault arcs existing electrical protection equipment cannot discriminate between motor starting current and arc fault current. An improved mine protection relay was developed by Lord & Pearson (1980) which discriminated between the mainly resistive arc fault and the inductive motor-starting circuit. A further safety device was designed by Lord & Davidson (1981) that monitors the temperature of the external surface of the enclosure and trips the earth leakage if temperature becomes excessive.

To the authors' knowledge, whilst CTI testing of materials is practiced in Australia on a routine basis niether of the other two protection techniques have found widespread application.

High-current Arcing

In United States underground coal mines all electrical equipment located close to coal being mined must be approved as "permissible" by the Mines Safety and Health Administration. Allen et al (1983) descibed the results of arcing tests made as part of an investigation to develop a permissible coal mine load centre for the US mining industry with a rating of 15 kV and 2,000 kVA. In these tests a single phase arc was drawn between two vertical copper rods spaced 152 mm apart inside a gas-tight cylindrical enclosure. Experiments were made with currets of up to 10 kA, with arc durations of up to 250 mS, and with air and methane-air mixtures inside the enclosure. The volume of the enclosure was varied by insertion of filling material. An interesting result from this work was that measured pressure rises due to internal arcing were found to be a maximum for an enclosure free volume of about 0.4 m^3 (all other conditions being the same), and that pressure rise due to arcing actually decreased with enclosure volume for enclosures with volumes less than this value.

Marinovic (1990) examined the propogation of hot particles, produced by vaporisation of thin copper wire by currents of up to about 25 kA, through flamepaths, and found that the minimum gap for flame transmission through the flamepath ocurred with a fault current of about 10 kA. A suggestion was made by an IEC (1989) working group that a special short circuit arcing test be made to verify non-transmission from flameproof enclosures has recently been considered by the International Electrotechnical Commission: no IEC recommendations have been made concerning this proposal at the time of writing.

Mesina (1986) attempted to derive equations that would enable characteristics of power system protection to be defined that would restrict the pressure rise due to high current arcing to not more than 1.8 bar. The basis of this work was that pressure rise due to arcing in air may be directly additive to that produced by a methane gas explosion.

Relevance to Australian Practice

It appears that the previous work by Lord and his co-workers in the UK on low current arcing deals specifically with flameproof enclosures, and is directly applicable to Australian conditions. The work done in the US and elsewhere on high current arcing is by no means as useful. The key experimental work done by Allen et al only provides information about pressure rise due to arcing, but no evidence is presented about the effect of internal arcing on flame containment. Later information indicated that calibration of gas analysers used in this paper were incorrect. Further no attempt was made to simulate realistic arcing conditions, and we felt that results that indicated low pressure rise due to arcing in small enclosures required confirmation.

As we considered that no previous work could provide the required assurance regarding the safety of flameproof enclosures of the type used in Australian mines we designed a series of experiments to quantify the effects of internal high-current arcing on flameproof enclosures. Volumes of the enclosures tested and test currents were chosen to be representative of those found in practice.

3. Internal Arcing Tests

Testing Procedures

The basic principle of the experiments conducted by the authors is illustrated by Figure 1. Arcs were initiated between three copper electrodes that had copper tungsten tips to reduce contact wear during arcing. One type of electrode was designed to maintain the arc in a fixed position and had a roughly hook shape as shown in Figure 1. Alternatively straight (parallel) electrodes were used that allowed the arc to lengthen in an uncontrolled way under the influence of self magnetic forces.

Conductors were taken through the walls of flameproof enclosures by standard flameproof plugs, and the arc was initiated by fusewire connected between the electrodes. The fusewire was vaporised when the high voltage supply was connected by a closure of an external circuit breaker, test current being limited by resistors and reactors (not shown in Figure 1) connected in series with the supply. The case of the enclosure under test was connected to laboratory ground, but neutral current was restricted to a low value by a reactor connected in the neutral as shown in Figure 1.

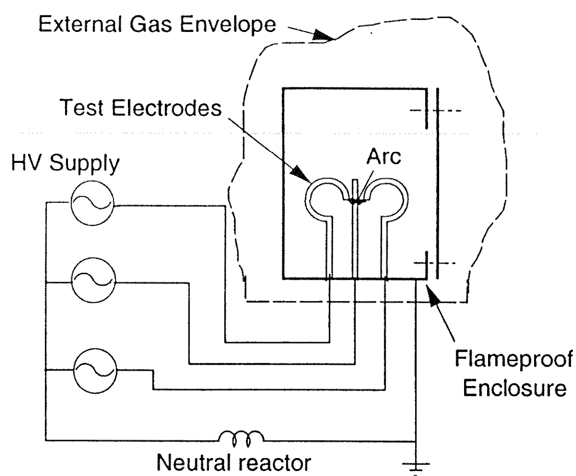

Figure 1. Electrical Connections to Flameproof Enclosures during Arcing Tests

Most arcing tests were made with an arc duration of approximately 300 ms: this was chosen as being the longest practical arcing time, and is seen as being the time of operation of back-up protection in the event of an earth leakage protection failure.

Prior to commencement of arcing tests all enclosures were tested to AS2480 (1986) to ensure conformance with the standard test requirements in force at the time when the experiments were done. These tests consisted of filling enclosures with an atmosphere with 9.8% methane in air and igniting the gas by a low energy spark. The internal pressure rises were recorded and each enclosure was subjected to a hydrostatic test at 150% of the recorded pressure as required in the standard. To test flame containment the enclosure was filled with an atmosphere with 8.7% methane and air: failure of flame containment was indicated by ignition of an envelope of similar gas following ignition of the internal gas by a spark. Pressure rises recorded during tests with spark ignition of air with 9.8% methane are included in Table 1.

Table 1. Pressure Rise in Enclosures with Spark Ignition of 9.8% Methane in Air

Volume (m^3)	Pressure Rise (Bar)	Volume (m^3)	Pressure Rise (Bar)
0.016	5.0	0.43	5.9
0.07	6.3	0.84	6.3
0.2	4.8	1.0	6.5
0.3	4.3	-	-

All enclosures sucessfully withstood the hydrostatic tests at 150% of the pressures shown in Table 1. No enclosure failed flameproof tests made with 8.7% methane and air: the enclosures were considered to be "flameproof" following the definition in AS2480 (1986)

Tests were made with arcing in air, with arcing in an atmosphere of air with 9.6% methane inside enclosures, and with arcing in an atmosphere of 8.7% methane inside enclosures. The later tests were done to determine where there would be flame transmission from the enclosure to an external explosive gas. The criterion for flame transmission was ignition of an external explosive gas mixture (8.7% methane and air): this external gas mixture was contained within a transparent plastic envelope as illustrated in Figure 1.

Arcing Tests

During arcing tests a monitoring computer recorded the following quantities: arc voltage and current, internal pressure rise within the enclosure (at two points), and external wall temperature using an IR detector. Total arc energy was subsequently calculated from current and voltage waveforms. No useful measurements of wall temperature were made, but the IR detector did provide an accurate indication of the instant at which external gas ignition occurred.

Some of the pressure rises due to internal arcing in air are shown in Table 2. The electrodes used in this test were of the hooked type illustrated in Figure 1. Distance between electrode tips was set at 69 mm with 1.1 kV and 3.3 kV supplies and 104 mm with 6.6 kV supply. These spacings being chosen to be equal to clearances recommended in equipment standards. Results in Table 2 show that there is considerable variability in the results but there is a clear trend for highest pressure rises to occur in the smallest enclosures. In the 0.016 enclosure with a 3.3 kV, 10 kV arc the internal pressure rise in an air atmosphere reached about 25 bar before the experimental plug connector was blown out of the enclosure in less than 62 ms.

Birtwhistle et al (1992) showed that the pressure rise in the flameproof enclosure was directly proportional to the total three phase arc energy supplied to the enclosure in all but the three smallest enclosures. In the 0.2 m^3 enclosure pressure rise was proportional to the square root of arc energy. In these smaller enclosures the arc may be in contact with the enclosure wall and energy may be lost from the arc by that path, or the higher pressures caused by arcing may cause greater pressure relief through the flamepath.

Table 2. Pressure Rise Due to Arcing in Air
(Arc Duration 300 milliseconds)

Enclosure Volume (m^3)	Electrical Supply		Pressure Rise (Bar)
	Line Volts (kV)	Current (kA)	
0.07	3.3	10	6.9
0.2	1.1	3	1.7
0.2	6.6	3	2.2
0.2	3.3	10	5.7
0.2	6.6	11	3.8
0.43	1.1	3	0.52
0.43	6.6	3	1.5
0.43	6.6	11	5.8
1.0	1.1	3	0.6
1.0	6.6	3	0.6
1.0	3.3	10	2.4
1.0	6.6	11	3.2

It is considered that the one high pressure rise shown in Table 2 in the 0.43 m^3 was probably due to abnormal lengthening of the arc. Tests with straight electrodes in fact indicated that arc energies were in most cases about twice the arc energy of comparable tests with hook-type electrodes that constrained the arc to an approximately linear path between the electrode tips. Lengthening of the arc was indicated by increase of arc voltage. We found that the peak pressure rise due to arcing in air had a strong correlation to the arc energy density where the energy density is simply the total arc energy divided by the enclosure volume.

Mesina (1986) suggested that protection equipment should act quickly to limit the pressure rise due to arcing to no more than 2.0 bar. To achieve this with our hook electrodes we found that the arc energy density would need to be limited to about 1500 kJ/m^3. We also found that arc energy was approximately proportional to arc duration. From data contained in the report by Birtwhistle et al (1992) we estimate that to restrict pressure rise to 2 bar with a three-phase, 10 kA, unconstricted arcing fault in a flameproof enclosure arc duration should be restricted to not more than:

Volume of enclosure in m^3 x 100 (milliseconds)

We emphasise that the above formula is an approximate relationship. It is not a precise statement of protection requirements, but it does indicate that we consider pressure rise to be strongly related to volume of the flameproof enclosure.

Arcing in Methane Atmospheres

In order to determine the effects on pressure rise of an atmosphere containing methane we have conducted a series of arcing experiments on enclosures filled with a mixture of 9.8% by volume of methane and air. The particular volume of methane was selected as it is considered to give the highest pressure rise according to flameproof standards current at the time of testing. Hook electrodes were used for all tests reported here.

Generally arcing in methane produced higher arc voltages and arc energies than did comparable arcing tests in air. The few tests when this was not the case had low current arcs (3 kA) that appeared to be extinguished by turbulence associated with the burning of the methane.

Pressure rise waveforms from a spark-ignited methane-air explosion, an arcing test in air and an arcing test in methane are shown in Figure 2: test current was 10 kA and the enclosure volume was 0.07 m^3. It is interesting to see from this Figure that the rate of pressure rise with arcing in methane is considerably greater than that due to the spark explosion or arcing in air. It is hypothesised that the presence of the large heat source of the arc causes the methane to burn at a much faster rate than was the case with spark ignition.

Figure 2 also shows that the peak pressure rise with arcing in methane is 9.5 bar compared with 4.8 bar produced by a spark explosion. Clearly arcing produces a more severe condition than that recommended by AS2480 (1986).

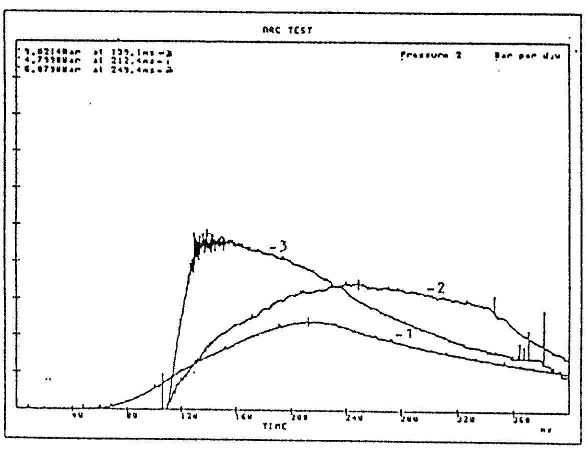

Figure 2. Pressure Rise in 0.07 m^3 Enclosure
(Axes: vertical 2 bar/div: horizontal 40ms/div)

(a) Spark ignition. 9.8 % CH_4 in air.
(b) Arc in air. 3.3 kV, 11 kA, 248 ms
(c) Arc in 9.8% CH_4. 3.3 kV, 10 kA, 275ms

In general test results showed that pressure rise due to 10 kA arcing alone exceeds that due to spark ignition of methane-air mixtures when enclosure volumes are less than about 0.2 m^3. Pressure rise in methane and air is always greater than pressure rise in spark ignited air-methane mixtures, and in 0.07 m^3 enclosures the ratio of pressure rise due to 10 kA arcing in air-methane to that due to spark ignition is about 2.

Insulation and Arcing

We observed that if organic material was placed close to the high current arc within a flameproof enclosure there is an increase in the internal pressure in the enclosure. Table 3 shows results obtained when insulating sheets were placed in the path of a 10 kA arc that was drawn between straight electrodes. Arc duration in all cases was approximately 300 ms.

Table 3. Pressure Rise - Insulation in Arc Path
Enclosure 0.07 m^3: Three-Phase 3.3 kV, 10 kA Arc

Insulating Material	Pressure Rise (bar)
No Insulation	6.1
Bakelite	10.4
PTFE	8.4
Cement Fibre *	17.0
Polycabonate	18.2

* comparative test only

Tests with polycarbonate insulation caused all bolts around the flamepath to fail, and the lid of the enclosure to be ejected a considerable distance.

A 10 kA arcing test was also carried out with straight electrodes inside a 0.2 m^3 enclosure that had been recovered from a mine and contained contactors, relays and interconnecting wiring. With 9.8% methane inside the enclosure a pressure rise of 8.9 bar was recorded, with copius emission of smoke and incandescent particles from the flamepath. Flames were emitted from the flamepath for tens of seconds after interruption of the test current.

Failure of Flame Containment

Table 4 summarises results of tests made to determine whether enclosures that have successfully past all requirements of AS2480 (1986) could withstand flame containment tests with internal arcing. Internal arcs were initiated within enclosures that were surrounded by an envelope that contained 8.7% methane in air. Tests were made both with the methane-air mixture, and with only air within the enclosures. The five smaller enclosures all had at least one external ignition, indicating that internal arcing imposes a greater risk than spark explosion. Failures were observed with air and with methane-air inside the enclosure, and with air and insulating material. The presence of insulation close to high energy arcs appeared to increase the possibility of flame containment failure.

Table 4. Results of Flame Containment Tests

Enclosure Volume (m^3)	Number Tests	Failures	Comments on Failures
0.016	1	1	Mechanical Failure
0.07	10	4	Mainly 10 kA arcs with insulation or 8.7% CH_4.
0.2	9	1	6.6 kV, 11 kA no gas or insulation
0.3	3	2	3.3 kA with gas 10 kA no gas
0.43	24	1	6.6kV, 11 kA with insulation
0.83	5	0	Moderate energy arcs only
1.0	9	0	High Energy Arcs

4.Implications for Mine Safety

The work described in this paper has demonstrated that external ignitions can be produced by internal arcing inside flameproof enclosures that have been certified to AS2480: further work is in progress to examine the performance of equipment certified to more recent standards (AS2380.2). We consider that it is likely that tests to the new standard will give similar results to those reported in this paper. It is fortunate that the co-incidence of explosive atmospheres in mines and internal arcing is likely to be small. An attempt has been made (Conn, 1987) to determine this risk for US coal mines, and further work is required to quantify the risk for Australian conditions.

We have shown conclusively that highest internal pressure rises will be produced with arcing in flameproof enclosures with small volumes. Pressure rise and risk of external gas ignition is increased by the presence of some types of electrical insulation materials close to the arc. To reduce the possibility of mechanical failure of enclosures, and possible flame transmission in explosive atmospheres we suggest that, in situations where the fault level approaches 10 kA, it would be advisable to ensure that the free volume of flameproof enclosures be not less than $0.3m^3$, unless the fault duration will be limited to a short time by high-reliability, fast-acting protection systems.

We have not studied the effects of internal arcing within dust-tight enclosures of the type commonly used to house electrical equipment in non-gassy areas of mines. We suggest that internal pressure rises due to fault arcing in such equipment must be limited to values that the enclosures can safely withstand. The data contained in this paper and more detailed reports (Birtwhistle et al (1992)) should be taken into account when determining safety of this type of equipment.

References

Allen, R., Conroy, G., Berry, R., and Gillemwater, R. (1983). High energy Arc Testing for the Development of a High Voltage Permissible Load Centre, Conference Record 1983 Mining Industry Technical Conference: Papers presented at the Third Conference, Michigan State University, Houghton, Michigan, June 1-3, 1983

Australian Standard 2380.2 (1992), Electrical equipment for explosive atmospheres.

Australian Standard 2480 (1986), Electrical equipment for explosive atmospheres.

Australian Standard 1136.1 (1988), Low Voltage Switchgear and Controlgear Assemblies. Part 1. General requirements.

Birtwhistle, D. and Byers, K. (1990). Arc fault containment in flameproof enclosures: Stage I, Rep.NERDDP, No.1461, 35pp

Birtwhistle, D., Byers, K., Crisp, J., and Das Gupta, S. (1992). Arc fault containment in flameproof enclosures (Stage II), Rep. NERDDP, No.1577, 164pp

Conn, W. (1987). "Estimating Maximum Arc Energies", Department of Labor, Mine Safety and Health Administration (United States), Engineering Report 87/021901

IEC (1989). International Electrotechnical Commission Document 31A(Sec) 39, Subcommittee 31A: Flameproof enclosures: final report of working group 2 on incandescent particles.

Lord, H., and Babero, L.P. (1975), Problems arising from the use of organic plastics materials in flameproof enclosures, Second International Conference on Safety in Hazardous Environments, December 1975, Institution of Electrical Engineers, London

Lord, H., and Davidson, L., (1981), Some aspects of explosion hazards in enclosure-protected electrical apparatus, Fire Protection Association, London, 1981

Luxmore, S. (1976), UK Health and Safety Executive Internal Memo SH 4/73/60, October, 1976

Marinovic, N. (1990). Electrotechnology in Mining (Book), Elsevier Science Publishers.

Mesina, J. M. (1986). Analysis: high current arcing fault protection(draft). US Mines Safety and Health Administration Approval and Certification Centre Report.

This paper contains material previouly published in the Paper: " Potential Hazards due to Fault Arcing in Underground Coal Mines" by D Birtwhistle & K Byers, Australian Coal Journal, No 40, 1993