Published as: B. Jensen and A.D.S. Gillies, Review of coal dust explosibility research. *Proceedings, Aus. Inst. Min. Met.*, 1994, 2 pp 9-14.

Review of coal dust explosibility research

By B JENSEN[1], Member and A D S GILLIES[2], Member

ABSTRACT

The paper presents a review of research in the area of explosible coal dust with respect to safety in the underground mining environment. Research over the last several decades has concentrated on generating dust clouds in small scale laboratory explosion chambers to study flammability limits and the physical and chemical variables which affect explosion propensity. The validity of this approach is discussed and the results obtained for a range of coal types compared.

INTRODUCTION

A practical understanding of the explosion hazards associated with dispersed coal dust and methane in terms of ignition dynamics, propagation characteristics and prevention is a prerequisite to establishing safe operating conditions in underground coal mines. Coal is a highly variable organic derivative and the theoretical predictions of dust explosibility based on thermodynamic or kinetic considerations by, for example, Nomura and Tanaka (1980) and Hertzberg, Cashdollar and Zlochower (1986) have been found to be difficult to apply practically (Torrent, Armada and Pedreira, 1988). Furthermore, mining techniques vary and add to the uncertainty in establishing safe conditions. Consequently, a practical approach to assessing mine safety has been to monitor what are deemed meaningful parameters during dust explosions under controlled conditions, thereby establishing a matrix of explosibility results over a range of several physical and chemical variables. Several designs of small laboratory explosion chambers and scaled experimental ducts have been developed for this purpose. By adopting this approach, a level of expertise has been gained which can recognise potentially dangerous combinations of conditions *in situ* and predict the level of stone dust addition required to inertise a specific coal type.

Research papers may be grouped into three distinct categories, namely, those relating to small scale laboratory testing, to explosion galleries designed as scale models of mines and to full scale experimental mines. Theoretical investigations have also been undertaken to determine the effects of size and configuration of explosion chambers on experimental data to establish the minimum acceptable volume of a test chamber (Siwek, 1980; Pickles, 1982; Pu *et al*, 1988; Bartknecht, 1989) and to relate test data obtained in a particular size and shape of chamber to those obtained in apparatus of different types and scale (Nomura and Tanaka, 1980). Research undertaken in several world centres has determined lean and rich limit concentrations, the effect of adding inertising dusts, flame velocity and propagation dynamics, static and dynamic pressures, ignition temperatures and energies for various coal types and the behaviour of hybrid mixtures. Given the scope and complexity of the subject of coal dust explosibility, it is with intent that the following review is restricted to literature concerned, either directly or indirectly, with investigations of flammability limits and ignition energies of coal dust and coal dust/methane hybrid explosible mixtures.

1. Senior Research Officer, Department of Chemical Engineering, The University of Queensland, Qld 4072.

2. Senior Lecturer in Mining Engineering, Department of Mining and Metallurgical Engineering, The University of Queensland, Qld 4072.

3. Original manuscript received March 1992.

4. Revised manuscript received November 1993.

Coal dust explosibility research is subject to many complicating factors and test data have at times been misleading or contradictory. There is, on occasion, wide disagreement between some authors. Mixtures of coal dust and air are inherently difficult to control and even with the same apparatus and experimental methods there may not be reproducibility from one test to the next. Furthermore, early research used explosion chambers which seriously underestimated dust explosibility and are therefore considered inadequate by modern standards. Problems related to small size, non-uniform dust dispersion, difficulty in measuring dispersed dust concentrations, inadequacies of the ignition source and lack of agreement with large scale mine gallery tests have resulted in the more recent development of larger and more sophisticated explosion chambers.

The Hartmann vessel developed at the United States Bureau of Mines in the 1930s (Hartmann, Nagy and Brown, 1943; Hartmann and Nagy, 1944; Hartmann, Nagy and Jacobsen, 1951) has a capacity of 1.2 litres. Chambers of this size have a large surface area to volume ratio and are subject to significant heat losses at the walls (Siwek, 1980). As a consequence, small volume chambers considerably underestimate explosion propensity (Woskoboenko, 1988). Twenty litre chambers of the the type developed more recently by the Bureau of Mines (Cashdollar and Hertzberg, 1985) are now routinely used as this is considered to be the minimum volume which does not seriously restrict the mechanism of explosion propagation (Siwek, 1980). There appears to be no significant bias in results obtained in these chambers at ignition energies in the intermediate range, up to approximately 1000 J. Above this energy level there is an observable overdriving effect on the propagation as the test volume is preheated and prepressurised by the ignitor (Hertzberg, Cashdollar and Zlochower, 1986).

There is some evidence to indicate that even with the larger chambers, the pneumatic method of dust dispersion and use of high energy ignitors cause turbulence which enhances heat and mass transport at the flame front (Pu *et al*, 1988; Bartknecht, 1989). This effect interferes with the combustion process and results in incomplete combustion. In this regard, Pickles (1982) proposed a theoretical model to explain the experimental observation that propagating explosions are more difficult to initiate in small laboratory scaled ducts than in full scale mine galleries. It was concluded that turbulent mixing at the flame front in the small ducts is too rapid in relation to the time needed for combustion of individual coal particles. As a result, the rate of flame propagation is constrained and explosion development is inhibited. Similar findings based on practical experimentation were reported by Pu *et al* (1988). They concluded that laminar flame propagation in small explosion chambers using pneumatic dust dispersion occurs at velocities which are between 10 to 100 times lower than the turbulent velocity and therefore proceeds close to conditions in which turbulent quenching by rapid mixing takes place. Therefore mixing of both energy and mass is a dominant controlling mechanism of combustion in small scale chambers. The high intensity and small scale turbulence is associated with confinement and does not occur to the same extent in large scale explosions. Thus explosion characteristics data obtained in a 950 litre chamber were shown to be more reliable than results from 26 litre and six litre vessels. Pickles (1982) suggested a cut-off diameter, estimated to be in the region of 0.5 m, below which it is markedly more difficult for a sustained propagation to occur in an experimental duct. Nevertheless, reasonably good agreement to mine gallery results has been achieved with the scaled ducts and laboratory chambers.

LEAN LIMIT CONCENTRATION RESEARCH

Factors affecting explosibility

The explosion potential of coal dust depends on a number of factors that include volatile content, ash content, moisture content and the energy and duration of the explosion initiator. The effective surface area, as determined by particle size, porosity and internal surface area is also an important variable, particularly for lower rank coal dusts (Woskoboenko, 1988). For the black coals, volatile content has been found to be the most significant factor in determining explosibility (Torrent, Armada and Pedreira, 1988; Hertzberg, Cashdollar and Zlochower, 1988; Jensen and Gillies, 1990). In the lower rank brown coals, particularly for smaller size fractions, moisture was shown to be the dominant factor, mainly by reducing the effective solid/air interfacial surface area of particles (Woskoboenko, 1988). The presence of methane further increases the explosibility of coal dust and this effect is more pronounced for dusts of low volatile content (Foniok, 1985; Tominaga *et al*, 1987). Research has established that methane and coal dust can act synergistically to form hybrid explosible mixtures (Foniok, 1985; Cashdollar *et al*, 1986; Jensen, 1990). In the hybrid mixture, the presence of each component effectively reduces the lean limit concentration of the other, so while each is present in concentrations which are considered safe, the mixture can be dangerous (Singhal, Stewart and Bacharach, 1987). The accepted value for the lean limit concentration of methane in air at room temperature is 5.0 per cent by volume. Various researchers have postulated that Pittsburg Seam coal, which is a Bureau of Mines standard research sample, or coals of similar rank and volatility, may explode with a lean limit concentration across the range from 5 to 310 g/m^3 (Hertzberg, Cashdollar and Opferman, 1979). More recent comprehensive testing by the Bureau of Mines identifies 90 g/m^3 as the lean limit for Pittsburg coal (Hertzberg, Cashdollar and Zlochower, 1986) and agreement appears to have been reached that an airborne concentration of 55 g/m^3 may be considered safe for this and similar bituminous coals (Hartmann, Jacobsen and Williams, 1954).

Equipment, techniques and results

A recurrent difficulty in early research on all scales was associated with measuring the dust concentration and ensuring uniformity of dust cloud formation. Researchers relied on calculating nominal concentrations based on either the known mass of introduced dust and the volume of the explosion chamber or by sampling. These methods assume that all the dust is dispersed uniformly in the chamber or gallery volume. This assumption could not be tested. Consequently a significant advance in dust explosion research followed the development of a direct reading opto-electronic concentration probe by the Bureau of Mines (Liebman, Conti and Cashdollar, 1977; Cashdollar, Liebman and Conti, 1981). A comprehensive investigation of the explosion characteristics of Pittsburgh Seam bituminous coal (37 per cent volatile matter) was undertaken by Hertzberg, Cashdollar and Opferman (1979) in parallel with the development of the dust probe. Using a 7.8 litre explosion chamber, lean limit concentrations were measured for nine size fractions over the range from 3 to 65 mm (average diameter) using ignitors of varying energies. The lean limit concentration of 135 g/m^3 at an ignition energy of 300 J was found to be virtually independent of particle size and was considered to be the asymptotic value unconstrained by ignition energy limitations. The authors therefore concluded that the accepted safe concentration of 55 g/m^3 for this coal appeared to be too low by a factor of about 2. They also found that low volatile matter Pocahontas Seam coal (16 to 18 per cent) was ignitable in concentrations above 250 g/m^3, despite not being ignitable in the smaller Hartmann vessel.

Earlier work in Poland by Cybulski (1975) on the dependence of lean limit concentration on particle size makes the findings of Hertzberg, Cashdollar and Opferman (1979) somewhat unclear. In the Polish tests, a strong inverse relationship was found between ignitability and particle diameter for 11 size ranges of Wujek 416 coal (36 per cent volatiles content) ranging from 0 - 2.5 µm to 50 - 60 µm. More recent Bureau of Mines papers by Hertzberg, Cashdollar and Lazzara (1981) and Hertzberg and Cashdollar (1986) report that lean limit concentrations are insensitive to particle diameter below 40 mm, although above this value the lean limit increases rapidly with increasing diameter. Indications are, however, that the different findings are explicable in terms of differences in ignition energy, the earlier results (Cybulski, 1975) being limited in this regard and therefore relating to dust ignitability properties rather than asymptotic lean limit concentrations which are, by definition, independent of ignitability (Jensen, 1990).

Another factor determining explosibility, particularly for the lower rank brown coals, is the effective surface area of the coal dust, which controls the rate of devolatilisation and combustion. This depends on particle size, porosity, moisture content and internal surface area (Woskoboenko, 1988). Most dust explosion models, for example as proposed by Hertzberg, Cashdollar and Zlochower (1986) or Bradley, Dixon-Lewis and El-din Habik (1989), assume that only the volatile matter is consumed in an explosion. Thus the role of the less reactive devolatilised particles (char) is considered to be essentially that of a heat sink as the combustion rate of the char is low enough to have an insignificant effect on flame propagation. The models therefore fail to consider the possible effects of the physical structure of the coal particle on explosibility. Woskoboenko (1988) has shown that this assumption may be invalid for lower rank coals since the oxygen reactivity of brown coal char is considerably higher than that of the bituminous chars. Thus physical structure, at least for brown coals, was considered to have two main effects on combustion. Firstly, the rate of devolatilisation, and therefore the rate of combustion, depends on the porosity of the coal. Secondly, the reactivity of the char substrate to direct oxidation increases markedly as the porosity, and hence surface area, increases. It was therefore concluded by Woskoboenko that for lower rank coals such as the Victorian brown coals used in the tests, the dust explosibility increases as the surface area increases due to the enhanced rate of devolatilisation and the increased participation of the resulting char in the flame front.

A 20 litre explosion chamber was developed by the Bureau of Mines (Cashdollar and Hertzberg, 1985) to overcome limitations in the maximum ignition energy that can realistically be used in small volume vessels. Tests in this chamber at ignition energies of 1000 J and 2500 J established a lower lean limit concentration between 90 to 100 g/m^3 for the Pittsburgh dust. A comparison of laboratory measured lean limit concentrations and mine gallery data was subsequently made by Cashdollar *et al* (1986) using the chamber at ignition energies up to 5000 J. A lean limit concentration of approximately 90 g/m^3 was found for Pittsburgh dust at ignition energies of 2500 J and 5000 J. This is in good agreement with the mine gallery value between 70 to 80 g/m^3 obtained at the Bruceton Experimental Mine. Importantly, this lower value is nearing the recommended safe concentration of 55 g/m^3 for this coal type. The low volatiles Pocahontas Seam samples also showed lower lean limit values of 100 g/m^3 and 140 g/m^3 with 5000 J and 2500 J ignitors respectively. These results compare well with the lean limit of approximately 100 g/m^3 obtained from the underground mine tests.

In order to address the restrictions imposed by the small size of laboratory explosion chambers and perceived limitations in ignition energies, Hertzberg, Cashdollar and Zlochower (1986) undertook a series of experiments to investigate the effects of a range of intermediate to high energy ignitors on the lean limit concentrations of methane and of Pittsburgh Seam coal dust. Pyrotechnic ignitors with nominal energies up to 5000 J were thus used in 20 litre and 120 litre explosion chambers. The rationale for this approach was expressed in the premise that an initial explosion front must exist before the capacity of the medium under investigation to sustain a propagation can be ascertained. To this end they used sufficiently strong ignitors to obtain results that were concluded to be independent of ignition energy and were therefore asymptotic lean limit values that were independent of ignition energy limitations. An asymptotic lean limit of 4.9 per cent by volume was obtained for methane in the 20 litre chamber across the intermediate range of ignition energies from approximately 160 to 1000 J. There was a marked decrease in the lean limit above this energy range indicating the overdriving effect of using stronger ignitors. The observed overdriving effect was nevertheless much reduced in the 120 litre explosion chamber. An asymptotic lean limit concentration for methane of 4.9 ± 0.1 per cent was then derived by combining the values obtained at intermediate ignition energies in the 20 litre chamber with values obtained at the highest energies in the 120 litre chamber. Using a similar method, a value of 90 ± 10 g/m^3 was derived for the lean limit concentration of Pittsburgh Seam coal dust.

Foniok (1985) found a strong decrease in the lean limit concentration of coal dust resulting from admixture with methane, based on tests with a range of coals with volatile contents from 11 to 46 per cent. The ignition energy used for all tests was 4500 J. Comparative tests on high lean limit concentration (low explosibility) coals, namely, 11 to 12 per cent volatile content brown coals and 46 per cent volatile coal inertised with 40 to 75 per cent limestone dust, demonstrated a dramatic decrease in dust lean limit concentration with increased methane addition. For example, one per cent by volume of added methane resulted in a decrease to 26 per cent of the original dust lean limit concentration; two and three per cent methane caused corresponding reductions in dust lean limits to 12 and five per cent respectively. Thus the relationship between methane addition and explosibility for these low volatiles and inertised coals was found to be nonlinear and it is evident that the effect of small concentrations of methane in enhancing dust explosibility is more pronounced for relatively inert coals. Furthermore, ignitability increased with increasing methane concentration, as shown by a decrease in the minimum ignition energy. It was therefore concluded that the addition of a low concentration of methane can change an inocuous coal dust into a very hazardous mixture with a low lean limit concentration.

Tests on hybrid mixtures by Cashdollar *et al* (1986) established the lean limit dust concentrations for Pittsburgh Seam coal over the methane concentration range between 0 and 5.0 per cent by volume at ignition energies of 1000 J and 2500 J. In these investigations an approximately linear inverse relationship was found between methane concentration and dust concentration at both ignition energies. This may reflect the relatively high volatile content of the Pittsburgh coal as the results compare well with those obtained by Foniok (1985) for dusts with 35 and 46 per cent volatiles.

Tominaga *et al* (1987) presented results from several Chinese and Japanese joint investigations, particularly concerning the effect of methane addition on coal dust explosibility. The authors indicated, however, that lack of experience in the research area caused their procedures and equipment to be less than satisfactory. Twelve samples of Chinese coals and three of Japanese, with volatile contents ranging from 27 to 44 per cent were tested using the Godbert-Greenwald furnace (Godbert and Greenwald, 1935), the Hartmann chamber, a 3.1 litre closed explosion chamber, a 10 m long scaled gallery and a 900 m long explosion duct. Results indicated that the ignition temperature for coal dusts in the absence of methane tended to decrease as the dust concentration increased. A generally higher ignition temperature was required for the lower volatiles dusts. Thus the reduced devolatilisation rates at lower ignition temperatures appear to be compensated to an extent by increased concentration and volatile content. However, no significant differences in ignition temperature were found with methane addition over the concentration range from 0 to 4.0 per cent by volume. Consistent with the earlier findings of Foniok (1985) and Cashdollar *et al* (1986), the results showed an approximately linear inverse relationship between the lean limit concentrations of coal dust and methane. The addition of 4.0 per cent methane by volume was found to reduce the lean limit concentration of the coal dusts by approximately 60 per cent, although the effect of methane addition was significantly more pronounced for lower volatiles content dusts. Small concentrations of methane were also found to increase the maximum explosion pressure, the rate of pressure rise and the velocity of flame propagation in the explosion gallery. Thus they concluded that there was an increased probability of explosion initiation associated with methane presence and the potential for more severe damage.

The effects of volatiles content, free moisture and incombustible solid matter (ash) in determining dust explosibility were extensively investigated by Cybulski (1975). In a series of 1134 experiments conducted in laboratory chambers and underground mine gallery at the Experimental Mine Barbara (Poland), samples from 43 seams with volatiles varying from 18.3 to 41.5 per cent were examined to establish the effect of volatiles on the lean limit. Results indicated a reduction in lean limit concentration from 133 to 41 g/m^3 as the volatiles content increased over this range. Free moisture is a factor in lowering dust explosibility and acts by decreasing dispersibility, increasing effective particle size by agglomeration and by absorbing heat. Woskoboenko (1988) showed that for brown coal dusts, moisture plays an important role by reducing the solid/air interfacial surface area of particles. Nevertheless, it was demonstrated by Cybulski (1975) that even relatively wet coal dust could be ignited and cause a violent explosion by using a sufficiently strong ignition source. With respect to incombustible matter, adsorbed moisture, ash and crushed roof and floor material were identified as components which contribute to the formation of dust clouds. Experimental results showed that lean limit concentration increases with an increase in incombustibles. Above 50 per cent incombustible content, the lean limit concentration was found to rise rapidly.

A predictive approach

Torrent and Pedreira (1987) and Torrent, Armada and Pedreira (1988) adopted a statistical approach to correlate explosibility of coal dusts to a composition index based on proximate and ultimate analyses. Samples from 21 seams were analysed for carbon, hydrogen, sulphur, moisture, ash and volatile content. Testing in an explosion gallery measuring 0.2 m in diameter and 4 m in length and a standard Hartmann vessel provided explosibility results which correlated well with dust composition. The explosibility criteria measured were lean limit concentration, maximum explosion pressure, rate of pressure rise and minimum ignition energy. A Godbert-Greenwald furnace was used to measure the minimum ignition temperature. The correlation coefficient obtained for the data was better than 0.98. The authors concluded that this could be further improved if several other parameters such as mean random reflectance of vitrinite and crucible swelling number (CSN) were included and the number of samples increased. Such an approach has the potential to provide an important predictive tool based solely on coal dust rank and provides a method for determining the relative flammability, that is, the level of stone dusting required to impede flame propagation and thereby render the coal safe. The successful application of theoretically derived values for stone dust addition in mine workings, however, depends on the accuracy of the original laboratory determined explosibility results. Indications are that the earlier results were limited with respect to ignition energy (Torrent and Pedreira, 1987). Consequently, the predicted values for inert dust additions were lower than they should have been and on-going research (Torrent, Armada and Pedreira, 1988) has shown that the values increase when based on explosion data obtained with stronger ignition sources. Thus the predictive model should be considered as a first step to apply small scale laboratory explosibility data to practical use in the underground mine environment.

RICH LIMIT CONCENTRATION RESEARCH

Background

Pickles (1982) proposed a model to describe the interaction of a cold particle of coal dust in the explosion front. Accordingly, combustion was treated in three separate stages, namely

1. conductive heating by hot combustion products from surrounding particles,
2. chemical decomposition and devolatilisation as the temperature rises, and
3. diffusion of oxygen into and combustion of the volatiles surrounding the particle.

At the explosion front, the rapid motion of the particle relative to surrounding particles, combustion products and atmospheric gases increases the rate of conductive heat exchange and oxygen flow. While it is useful to treat the three stages separately, it is evident that there will be some overlap between them. By assuming a cold particle temperature of 300°K, a temperature of 1800°K for the combustion products and an average temperature of 1200°K for devolatilisation and combustion, a combustion time of 15 ms was estimated for particles with diameters of 50 μm. The model fails to consider the effects of radiative and convective heat transfer. Nevertheless, it provides a basis for describing the energy balance and physical threshold conditions which must apply for a propagation to be sustainable.

In a propagating explosion, the absorption of heat by cold particles at the explosion front is countered by the outflow of heat energy during the combustion of devolatilisation products from surrounding particles. It is evident that the energy flux linking the two processes must be maintained above a certain limiting value for combustion to be sustainable. It is also evident that explosion sustainability is dependent on both the rate of energy input from the combustion stage and on the energy required to elevate the temperature of cold particles to the devolatilisation and combustion stages. That is, the specific energy and spatial distribution of particles must be adequate to match the specific heat, latent heat of vaporisation and ignition energy requirements at the explosion front for propagation to be sustained.

It has been established that a minimum concentration of coal dust must be present to sustain an explosion. This represents the lean limit. Addition of dust above this concentration appears to have a minimal effect on explosibility until the stoichiometric concentration is reached. As the concentration progressively exceeds this value, research has shown that the surplus coal dust acts as an explosion inhibitor and causes a reduction in the reaction rate by absorbing heat from the surroundings while not contributing an energy input through combustion. Hence the combustion energy flux is disrupted as the surplus fuel becomes a heat sink and devolatisation decreases. Evidence for this has been found by Smoot, Horton and Williams (1976) who showed that the temperature and devolatilisation rate within the flame front decrease with increasing concentration. The CO/CO_2 ratio also increases in richer flames. Devolatilisation was found to be a strong function of dust concentration. At a specific (and high) concentration, the excess coal dust absorbs sufficient heat from the surroundings to prevent further flame propagation. This is the rich limit concentration.

Relatively little research has been undertaken in the area of coal dust rich limit concentrations as mine explosion safety concerns have been largely directed towards lean limit research. An understanding of the rich limit characteristics of explosible dusts, however, is pertinent to industrial processes involving the pneumatic transport of these materials. The lack of experimental work is also due to the inherent difficulty in determining rich limit concentrations of dust and air mixtures. Problems include the difficulty in generating high concentrations of dust with uniform distribution (Mason and Saunders, 1975) and in measuring dust concentration and other variables at these concentrations (Deguingand and Galant, 1981). There is also disagreement among authors as to the existance of a true rich limit for dusts. For example, Slezak, Buckius and Krier (1986) indicate that true dust rich limit concentrations may be undefinable as a result of the practical difficulties in obtaining homogeneous mixtures at high concentrations. The notion of a true rich limit for coal dust is disputed by Hertzberg and Cashdollar (1986) who assert, based on a thermodynamic model, that the absence of rich limits is characteristic of all dusts. Their report indicates, however, that the devolatilisation rate becomes a limiting factor as dust concentration is increased, as was shown experimentally by Smoot, Horton and Williams (1976). The authors also indicate that at very high dust concentrations the excess unreacting fuel will provide a sufficient heat sink for flame propagation to cease.

Research methods and results

Hertzberg, Cashdollar and Zlochower (1986) were unable to find a rich limit for Pittsburgh coal dust to concentrations as high as 4.0 kg/m^3. This is in contrast to results found by Smoot, Horton and Williams (1976) who observed rich limits for Pittsburgh and Pocahontas seam samples. Flames were found to be difficult to stabilise at dust concentrations above 1.2 kg/m^3 using a downward flow, 102 mm flat flame burner (Horton, Goodson and Smoot, 1977). This concentration was interpreted as the apparent rich limit. Increased particle size was found to increase the rich limit concentration in these experiments. Slezak, Buckius and Krier (1986) found evidence for a rich limit for Pittsburgh coal using a rotating horizontal combustion tube (Slezak *et al*, 1983). Observations with pulverised Pittsburgh coal showed that flame propagation occurred only in regions of the tube where the concentration was below approximately 1.5 kg/m^3.

Deguingand and Galant (1981) studied rich limits in an eight litre explosion chamber modified from the design of Hertzberg, Cashdollar and Opferman (1979). Two size fractions, namely, 13 μm and 50 μm of 35 per cent volatile matter Freyming coal (comparable to Pittsburgh coal) were used in the investigation. Criteria used to identify the rich limit were peak pressure, maximum rate of pressure rise and residual gas concentration measurements. Dust concentration was determined by nominal calculation. The investigation identified 3.5 kg/m^3 as the rich limit for this coal, although the authors question the reliability of the experimental technique, particularly with respect to concentration evaluation in the region of the electrical discharge ignitor. The data show only a weak relationship between rich limit concentration and particle size. Unexpectedly, the gas analysis showed a decrease in the CO/CO_2 ratio with increasing dust concentration from 500 g/m^3 to the rich limit.

Woskoboenko (1988) found upper explosive limits for Morwell (Victorian brown) coal dust in a 20 litre spherical chamber using both air dried and moisture free samples. A value of 7 kg/m^3 was found for the air dried sample (14.1 per cent moisture; 49.5 per cent volatiles). The moisture free sample was still explodable at the maximum concentration attainable in the explosion chamber, namely, 10 kg/m^3. The author qualified these results and indicated that they are a guide only due to the difficulty in obtaining uniform dust concentrations in the chamber, largely because of agglomeration and turbulence effects.

While there may be disagreement over the occurrence of a true rich limit and the nature of the mechanism of explosion inhibition at high dust concentrations, there is a common recognition that excessive loadings of suspended explosible dust are inhibitory to explosion propagation. There is also a recognition that at very high dust concentrations, the excess fuel does not to participate in the exothermic combustion stage of explosion and instead acts as a heat sink.

CONCLUSION

Coal dust explosibility is subject to many physical and chemical variables. Research in the area over the last several decades has focused on the use of small laboratory explosion chambers and scaled galleries. The more recent equipment has provided explosibility data for a variety of coal dusts which show good agreement to data obtained from full scale mine tests. Research has shown that volatile content is the most significant variable in determining coal dust explosibility. Other variables in this regard include particle size, ash content and moisture content. Dust explosibility is also subject to several external variables including the energy, temperature and duration of the ignitor and the presence of methane. Much research has been directed towards establishing lean limit concentrations for a number of coal dust types with the aim of establishing safe operating conditions in underground mines. While there may be disagreement over the occurrence of a true rich limit and the nature of the mechanism of explosion inhibition at high dust concentrations, there is a common recognition that excessive loadings of suspended explosible dust are inhibitory to explosion propagation.

REFERENCES

Bartknecht, W, 1989. *Dust Explosions: Source, Prevention, Protection,* 270 p (Springer Verlag: Berlin; New York).

Bradley, D, Dixon-Lewis, G and El-din Habik, S, 1989. Lean flammability limits and laminar burning velocities of CH_4-air-graphite mixtures and fine coal dusts, *Combustion and Flame*, 77: 41-50.

Cashdollar, K L, Liebman, I and Conti, R S, 1981. Three Bureau of Mines optical dust probes, US Bureau of Mines Report of Investigations 8542, 26 p.

Cashdollar, K L and Hertzberg, M, 1985. 20L explosibility test chamber for dusts and gases, *Journal of Physics E: Review of Scientific Instruments*, 56(4): 596-602.

Cashdollar, K L, Sapko, M J, Weiss, E S and Hertzberg, M, 1986. Laboratory and mine dust explosion research at the Bureau of Mines, in *Industrial Dust Explosions ASTM STP 958* (Eds K L Cashdollar and M Hertzberg), pp 107-123 (American Society for Testing and Materials: Philadelphia).

Cybulski, W, 1975. *Coal Dust Explosions and Their Suppression*, (Foreign Scientific Publications Department of the National Center for Scientific, Technical and Economic Information: Warsaw, Poland).

Deguingand, B and Galant, S, 1981. Upper flammability limits of coal dust-air mixtures, in *The Eighteenth Symposium (International) on Combustion*, pp 705-715 (The Combustion Institute: Waterloo, Canada).

Foniok, R, 1985. Hybrid dispersive mixtures and inertized mixtures of coal dust - explosiveness and ignitability, *Luft*, 45(4): 151-154.

Godbert, A L and Greenwald, H P, 1935. Laboratory studies of the inflammability of coal dusts: Effect of fineness of coal and inert dusts on inflammability of coal dusts, *US Bureau of Mines Bulletin*, 389: 29 p.

Hartmann, I, Nagy, J and Brown, H R, 1943. Inflammability and explosibility of metal powders, US Bureau of Mines Report of Investigations 3722, 38 p.

Hartmann, I and Nagy, J, 1944. Inflammability and explosibility of powders used in the plastics industry, US Bureau of Mines Report of Investigations 3751, 44 p.

Hartmann, I, Nagy, J and Jacobsen, M, 1951. Explosive characteristics of titanium, zirconium, thorium, uranium and their hydrides, US Bureau of Mines Report of Investigations 4835, 16 p.

Hartmann, I, Jacobsen, M and Williams, R P, 1954. Laboratory explosibility of American coals, US Bureau of Mines Report of Investigations 5052, 9 p.

Hertzberg, M, Cashdollar, K L and Opferman, J J, 1979. The flammability of coal dust-air mixtures: Lean limits, flame temperatures, ignition energies, and particle size effects, US Bureau of Mines Report of Investigations 8360, 70 p.

Hertzberg, M, Cashdollar, K L and Lazzara, C P, 1981. The limits of flammability of pulverized coals and other dusts, in *Eighteenth Symposium (International) on Combustion*, pp 717-729 (The Combustion Institute: Waterloo, Canada).

Hertzberg, M and Cashdollar, K L, 1986. Introduction to dust explosions, in *Industrial Dust Explosions ASTM STP 958* (Eds K L Cashdollar and M Hertzberg), pp 5-32 (American Society for Testing and Materials: Philadelphia).

Hertzberg, M, Cashdollar, K L and Zlochower, I A, 1986. Flammability limit measurements for dusts and gases: ignition energy requirements and pressure dependences, in *Twenty-First Symposium (International) on Combustion*, pp 303-320 (The Combustion Institute: Munich).

Hertzberg, M, Cashdollar, K L and Zlochower, I A, 1988. Effect of volatility on dust flammability limits for coal, gilsonite and polyethylene, in *Twenty-Second Symposium (International) on Combustion*, pp 1757-1765 (The Combustion Institute: Seattle).

Horton, M.D, Goodson, F P and Smoot, L D, 1977. Characteristics of flat, laminar coal-dust flames, *Combustion and Flame*, 28: 187-195.

Jensen, B and Gillies, A D S, 1990. An experimental approach to characterizing explosible coal dust/methane atmospheres, in *Proceedings of the Minesafe International 1990 Conference*, pp. 771-775 (Chamber of Mines and Energy: Perth).

Jensen, B, 1990. An experimental approach to the determination of coal dust/methane explosibility on longwall faces, MEngSc Thesis, Department of Mining and Metallurgical Engineering, The University of Queensland.

Liebman, I, Conti, R S and Cashdollar, K L, 1977. Dust cloud concentration probe, *Journal of Physics E: Review of Scientific Instruments*, 48(10): 1314-1316.

Mason, W E and Saunders, K V, 1975. Recirculating flow in vertical columns of gas-solid suspension, *Journal of Physics D: Applied Physics*, 8: 1674-1685.

Nomura, S and Tanaka, T, 1980. Prediction of maximum rate of pressure rise due to dust explosion in closed spherical and nonspherical vessels, *IEC Process Design and Development*, 19: 451-459.

Pickles, J H, 1982. A model for coal dust duct explosions, *Combustion and Flame*, 44: 153-168.

Pu, Y K, Jarosinski, J, Tai, C S, Kauffman, C W and Sichel, M, 1988. The investigation of the feature of dispersion induced turbulence and its effects on dust explosions in closed vessels, in *Twenty-Second Symposium (International) on Combustion*, pp 1777-1787 (The Combustion Institute: Seattle).

Singhal, R K, Stewart, D B and Bacharach, J P L, 1987. Frictional ignition control, *Colliery Guardian*, 235(5): 176-182.

Siwek, R, 1980. Experimental methods for the determination of explosion characteristics of combustible dusts, in *Third International Symposium on Loss Prevention and Safety Promotion in the Process Industries*, Vol 2 pp 839-850, (Swiss Society of Chemical Industries: Basle).

Slezak, S E, Fitch, D J, Krier, H and Buckius, R O, 1983. Coal dust flame propagation in a laboratory flammability tube, *Combustion and Flame*, 54:103-119.

Slezak, S E, Buckius, R O and Krier, H, 1986. Evidence of the rich flammability limit for pulverized Pittsburgh Seam coal-air mixtures, *Combustion and Flame*, 63: 209-215

Smoot, L D, Horton, M D and Williams, G A, 1976. Propagation of laminar pulverized coal-air flames, in *The Sixteenth Symposium (International) on Combustion*, pp 375-387, (The Combustion Institute: Cambridge).

Tominaga, T, Matsuura, S, Komai, T and Isei, T, 1987. Coal dust explosion characteristics under atmosphere with methane gas coexistence, in *Safety in Mines Research - Proceedings of the 22nd International Conference of Safety in Mines Research Institutes* (Ed. Dai Guoquan), pp 411-421, (China Coal Industry Publishing House, Beijing).

Torrent, J G and Pedreira, R A, 1987. Small-scale experiments for measuring coal dust explosion propagation, in *Safety in Mines Research - Proceedings of the 22nd International Conference of Safety in Mines Research Institutes* (Ed. Dai Guoquan), pp 441-446, (China Coal Industry Publishing House: Beijing).

Torrent, J G, Armada, I S and Pedreira, R A, 1988. A correlation between composition and explosibility index for coal dust, *Fuel*, 67: 1629-1632.

Woskoboenko, F, 1988. Explosibility of Victorian brown coal dust, *Fuel*, 67: 1062-1067.