Risk Assessment Based Stone Dusting and Explosion Barrier Requirements

By

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Introduction

For many years, mines regulations in Queensland and New South Wales specified the level of stone dusting and explosion barrier protection required for underground coal mines. In precise origins of the regulations are unclear but almost certainly stem from investigations carried out in Europe and the UK during the 1950's and 1960's. The result was a set of rules and regulations that, if followed by a mine, were considered adequate to prevent the propagation of a coal dust explosion. Generally, these rules were accepted without criticism or thought for the limitations of the control methods beyond the practicalities of installation and compliance. This in turn led to criticism that the regulations were out of touch and often unworkable, with little consideration for the effectiveness of the controls established.

In recent times, there has been a move away from a high level of prescriptive regulation, towards risk management and its application to all aspects of underground coal mining. As in so many areas, there is a need to develop a means of assessing the risks associated with coal dust explosions and the most effective means of control, if user risk assessments are to be considered credible.

ACIRL has undertaken a number of projects, largely funded by ACARP, to investigate and review methods used to suppress and prevent coal dust explosions. This work has investigated the use of explosion barriers and the effectiveness of stone dust and has lead to a much better understanding of the effectiveness of the traditional controls for coal dust explosions. The knowledge gained has been used to develop a quantitative method of risk assessment of controls for coal dust explosion suppression.

Background

Coal dust explosions occur when fine coal particles become airborne and are ignited by some means. In a coal mine, the precursor to a coal dust explosion is usually the ignition of a quantity of methane. The resulting flame travels through the available fuel leaving behind hot expanding gases. In the presence of some degree of confinement from the roof floor and sides, the gases cannot expand in all directions and a pressure wave is produced that accelerates the flame and causes fine coal dust to become airborne. This is in turn, ignited by the flame that lags behind the pressure front, further driving the pressure front along and raising more dust ahead of the flame front. Until there is a break in this cycle of raising then igniting coal dust, the explosion continues to propagate generating destructive pressures and large quantities of irrespirable and toxic gases. Ultimately, a coal dust explosion could pass through the entire coal mine until it reached the surface.

The obvious point at which to prevent a coal dust explosion is at the start with the initial gas ignition. This requires dispersal of methane to prevent the formation flammable mixtures and the elimination of ignition sources for methane. Controls at this level include maintenance of adequate ventilation, methane gas drainage, monitoring of methane concentrations, cessation of operations during periods of gas accumulations, and the use of intrinsically safe, flameproof and non-incendive equipment.

To prevent a gas ignition developing into a coal dust explosion and propagating throughout the mine requires the elimination of flammable dust accumulations in the workings and extinguishment of the flame. The main means used to eliminate flammable dust accumulations is stone dusting which works by diluting coal dust with ground limestone to the point at which it will no longer combust when raised into the air as a dust cloud. In the event that stone dusting is inadequate to prevent ignition of the roadway dust, an explosion barrier adds more stone dust or water to the airborne dust to extinguish the flame.

As the usual initiating event for the development of a coal dust explosion is the ignition of a small amount of methane, the mine requires protection against ignitions initiated at face areas of a panel. The initial methane ignition forces clouds of roadway dust into the air in any entries connected to the face and the coal dust explosion will propagate in any one of these. Once a coal dust explosion has begun to propagate in a panel entry, it can only be stopped by those systems and treatments already in place. The effectiveness of those systems and treatments will determine whether the explosion is suppressed or whether it continues to propagate all the way to the surface of the mine, with the attendant losses.

The Requirements for a Risk Assessment Method

In the past, it has just been accepted that the standards specified by the relevant Mines Regulations were adequate for the prevention and suppression of coal dust explosions. No consideration was given to the residual risks associated with compliance nor to variations from the Regulations. With a move toward risk management, there is a need to be able to assess the risks associated with any scheme of coal dust explosion suppression so that alternative strategies can be assessed and compared with confidence.

Risk Assessment Method

The risks associated with a coal dust explosion in a panel can be assessed by determining:

1. The frequency of gas ignitions in the panel
2. The probability of developing a coal dust explosion as a result of the gas ignition
3. The probability of propagation down each panel entry, which in turn is determined by a combination of:
    a. The probability of propagation through an area of trickle stone dusting
    b. The probability of propagation through an area of campaign stone dusting
    c. The probability of propagation through a discrete explosion barrier, and
4. The consequences and risk of propagation to different positions in a panel

Each of these aspects will be considered below and then used in a worked example to illustrate the application of the risk assessment method

Frequency of Gas Ignitions at the Face.

An assessment of the reported gas ignitions in Australian for the period 1988 to 2000, shows 51 reported gas ignitions (1), of which 12 occurred on longwall faces, and 35 on continuous miner development sections. During the same period, it is estimated that there were about 37 operating longwall faces (37 mines * 1 face per mine) and about 126 development faces (63 mines * 2 faces per mine).

The resulting frequency of face ignitions for Australian mines is therefore about 0.027/face/year on a longwall face, and 0.023/face/year on a development face.

In the USA, for the period 1988 to 1994, there were 202 gas ignitions on longwall faces (2). It is estimated that on average during this period there were 90 operating longwall faces in the USA. This gives an average frequency of 0.32 ignitions/face/year, which is significantly higher than the Australian experience.

For the purposes of this analysis, the average rate of gas ignitions on a coal face will be taken to be 0.025 ignitions/face/year irrespective of the type of production. This equates to one ignition on a face every forty years.

Probability of Developing a Coal Dust Explosion as a Result of the Gas Ignition

The next step in assessing the risk associated with a coal dust suppression system is to estimate the probability that a gas ignition develops into a coal dust explosion. This can be done by considering the 51 ignitions referred to above. Assuming that:

1. None of these ignitions developed into a coal dust explosion, and,

2. There should be a high degree of confidence that the future actual behaviour is not worse than the predicted behaviour,

Then the probability of triggering can be calculated in the following manner.

Let $Pr(1/1)$ = Probability of a gas ignition resulting in a coal dust ignition

$Pr(51/0)$ = Probability 51 explosions do not result in a coal dust ignition

If the degree of confidence required is 98% then:

$$Pr(51/0) >= 1-0.98 >= (1-Pr(1/1))^{51}$$

$$(1-Pr(1/1))^{51} <=0.02$$

$$1-Pr(1/1) <= 0.02^{(1/51)} = 0.926$$

$$Pr(1/1)<= 0.074 \text{ or } 7.4\%$$

Given that a gas ignition has resulted in a coal dust ignition, the dust explosion suppression systems must come into play to prevent the explosion propagation. At this stage, any explosion will be moving away from the point of ignition and into the panel roadways or gateroads off the longwall face. Techniques used to prevent propagation in through these areas are trickle stone dusting, campaign stone dusting (with or without trickle dusting) and explosion barriers. The effectiveness of these methods can be expressed as the probability of propagation through the control, with lower probabilities representing higher effectiveness.

Probability of Propagation – Trickle Stone Dusting

During the normal action of coal mining, large quantities of fine coal dust are generated and become airborne. This fine dust enters the panel returns and tends to settle out on the ribs and roof, but predominantly on the floor. In the event of an explosion, this dust is easily disturbed and lifted back into the air where it is ignited and permits the propagation of a coal dust explosion. Trickle dusting is the practice of blowing a steady stream of fine stone dust into the panel return roadway in an attempt to render this dust incombustible, and therefore incapable of propagating a coal dust explosion.

The effectiveness of a zone treated by trickle dusting is determined by the proportion of stone dust in the resulting roadway dust mixture (stone dust and coal dust combined). The proportion of stone dust in roadway dust is determined by the settling characteristics of the stone dust and coal dust, the delivery rate of stone dust and the burden of coal dust entering the returns.

From recent research conducted in Australia (2) it appears that the minimum inerting requirements are about 85% total incombustible content in the absence of methane. (Total incombustibles in roadway are the stone dust plus moisture and ash in the coal). The requirement for stone dusting is increased by about 5% TIC for each 1% of methane present. Cybulski (3) conducted extensive investigations regarding the effectiveness of stone dusting and explosion barriers. Figure 2 shows the probability of a coal dust explosion propagating through a 200m and a 400m long zone of stone dusting, in relation to the incombustible/stone dust content of the roadway dust. Note that there is very little margin in stone dusting requirements between a low and a high probability of propagation.

The incombustible content can be determined directly from fallout measurements downwind of the trickle duster and used to determine the effectiveness by reference to Figure 2. A correction has to be made for the presence of methane, which requires an increase of 5% in incombustible content for each 1% of methane present. After determining the incombustible content of the fallout dust, this is reduced by 5% for each 1% of methane to calculate an equivalent incombustible content that can be used in Figure 1.

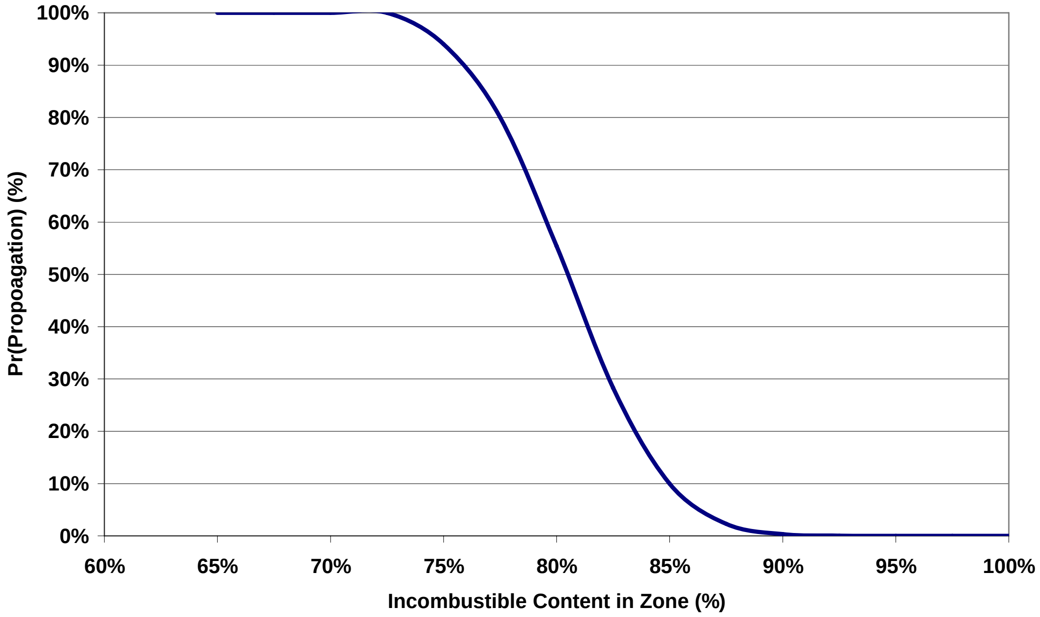

Figure 1 – Probability of Propagation Through a 200m Zone of Stone Dusting.

A conservative approach, to calculating the probability of propagation through a zone greater than 200m long, is to divide the zone into a number of zones each 200m long and determine the probability of propagation in each of these zones. The probability of propagation through the complete zone is the product of the individual probabilities.

If a zone is also protected by campaign stone dusting, the method described below should be used.

Probability of Propagation – Campaign Stone Dusting

Campaign stone dusting is used periodically to place a layer of pure stone dust over a large area of a roadway to cover any existing roadway dust. It is intended to isolate any explosible/combustible dust accumulation beneath sufficient stone dust to prevent it becoming airborne in an explosion and contributing to propagation.

Only a relatively thin layer of dust is lifted from the floor during an explosion and contributes to the fuel driving its propagation. Testing conducted by the USBM (4) showed that only the top 2 to 4mm of floor dust is lifted during an explosion. If the top layer of roadway dust is combustible, it will support the propagation of a coal dust explosion. Therefore the effectiveness of campaign stone dusting depends upon the frequency of application of fresh stone dust, the fallout rate and the incombustible content of float dust and the depth of scouring that takes place.

After a programme of stone dusting, float dust will immediately begin to accumulate on top of the new stone dust. In the absence of methane, when the incombustibles content of the top, say 2mm, of accumulated float dust plus stone dust roadway is less than 90% (see Figure 1 above), there is a chance that a coal dust explosion could propagate through the zone. As more float dust accumulates the incombustible content of the top 2mmm will continue to fall until it is the same as the incombustible content of the airborne float dust. At this time, the probability of propagation has reached a maximum and will remain at this value until the next round of campaign stone dusting takes place. If the area is subject to trickle dusting, the float dust will consist of coal and stone dust and will have some level of incombustibles. If there is no trickle dusting, the float dust that accumulates will be pure coal dust.

Consider a roadway in which campaign stone dusting is carried out every 20 days, there is no trickle dusting, the average methane content is 1%, and the fallout rate for float dust is 0.125mm/day. After 20 days there will be a layer of pure coal dust of 2.5mm on top of the previous campaign stone dust (see

Figure 2). After about 1 day, the incombustible content of the top 2mm will have fallen to 95% (90+5), at which time the probability of propagation is greater than zero. After about 3.5 days, the incombustible content of the top 2mm will have fallen to 78% (73+5), at which time the probability of propagation is 1 and can increase no further. The overall probability of propagation through the zone between sessions of campaign stone dusting is then easily calculated form the areas of the last graph in Figure 2, in this case 89%.

There are a number of possible scenarios that have to be considered in assessing the probability of propagation through an area of campaign stone dusting. The example above assumed that no trickle dusting was taking place. This will be the case in any intake roadway. In a panel return, it is more likely that a trickle dust will be operating in which case consideration must be given to the incombustible content of the fallout dust. This is easily measured along with the fallout rate, by some simple fallout tests. The incombustible content of the top layer is then easily determined and the probability of propagation can be assessed.

Again, the conservative approach to calculating the probability of propagation through a zone greater than 200m long is to divide the zone into a number of zones each 200m long and determining the probability of propagation in each of these zones. The probability of propagation through the complete zone is the product of the individual probabilities.

Probability of Propagation – Discrete Explosion Barrier

An explosion barrier consists of a series of stone dust shelves or water filled tubs suspended in a length of mine roadway. In the event of an explosion, the shelves or tubs are constructed in such a way that the explosion pressures propel the dust or water into the air. If sufficient dust or water is present, the effect is to extinguish the flame that arrives shortly after the pressure wave.

The principal factors determining the effectiveness of an explosion barrier are the distance between the start of the barrier and the point of ignition, and the mass of stone dust or water in the barrier. This was investigated extensively by Cybulski (3). Based on many explosion barrier trials, Figure 3 shows the conditions necessary to stop an explosion using a stone dust or water barrier. The area above the upper curve represents the conditions required to stop an explosion within the length of the barrier i.e. “on the spot”. Below the lower curve, the barrier failed to stop the explosion and in the area between the two curves the flame extended beyond the end of the barrier but was stopped.

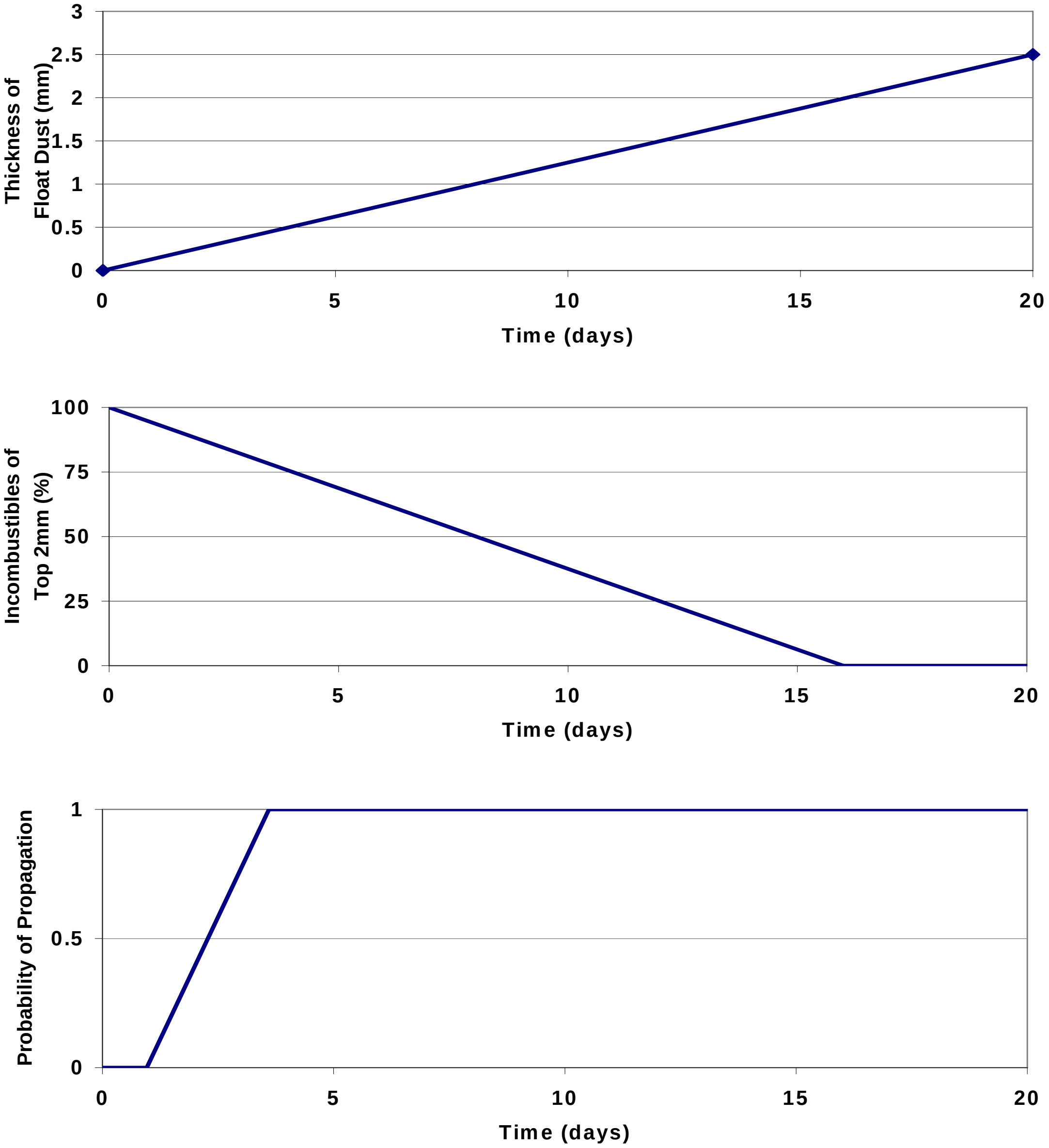

Figure 2 – Determination of the Probability of Propagation Through a Zone of Campaign Stone Dusting

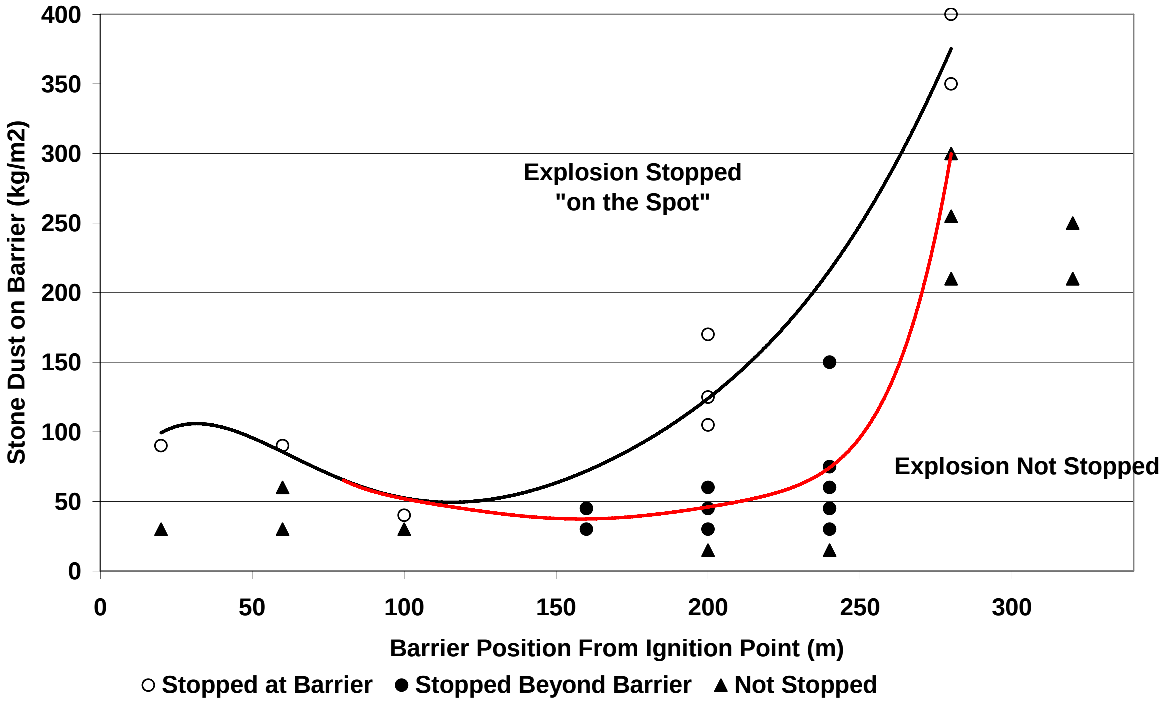

Figure 3 – Effectiveness of Discrete Explosion Barrier (after Cybulski (3))

The probability of propagation through an explosion barrier can then be assessed by reference to Figure 3. In the event that the combination of barrier loading and distance from the ignition source lies above the upper curve the probability of propagation is zero. During the normal course of mining, however, the distance between the likely source of ignition and the barrier is always changing as the face advances/retreats and the barrier is relocated. Further, the area in which ignition is likely to occur may be extensive as on a longwall extraction face. These need to be considered when attempting to determine the probability of propagation of an explosion from a panel, through an explosion barrier.

Consider a longwall face, say 200m wide with a stone dust barrier of 400 kg/m^2 in one roadway and located 100m from the face (see Figure 4). At 400 kg/m^2 the barrier will provide protection against an explosion originating up to 280m from the inbye end of the barrier. If the face is considered to be the likely area for ignition, the barrier will only provide protection for ignitions on the first 180m of the face (280-100). Ignitions that originate in the last 20m of the longwall face will not be suppressed by the barrier. The probability of propagation through the barrier in this position is therefore 10% (20/200).

When the barrier is relocated outbye by another 100m to 200m from the face, the barrier only provides protection for ignitions that occur on the first 80m of the face. The probability of propagation is now 60% (120/200). The probability of propagation for this configuration of barrier, face length and approach distances, is therefore 35% (60/2+10/2).

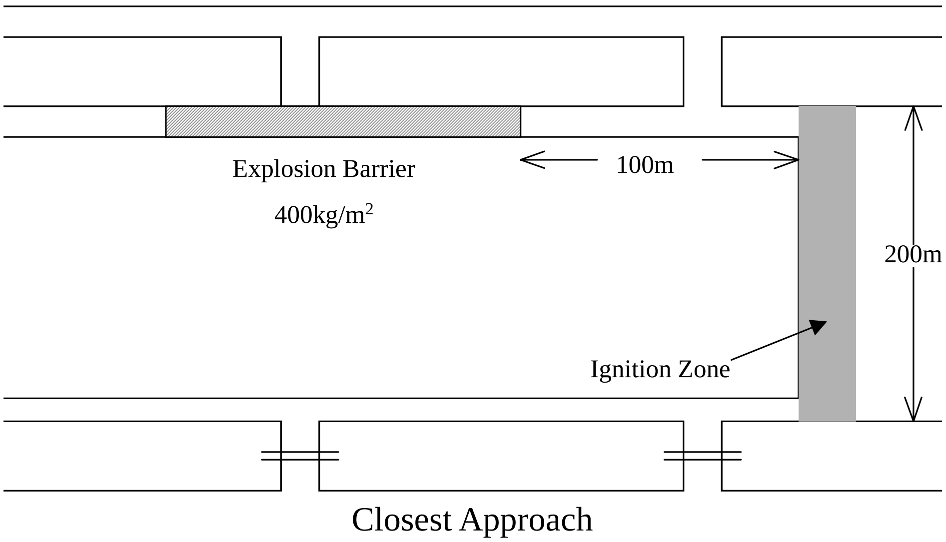

Figure 4 – Explosion Barrier Configuration

Probability of Propagation – Combinations of Controls

Often in panel entry, more than one suppression method as described above will be used. Typically, this will involve the installation of an explosion barrier in combination with a trickle duster, or with campaign stone dusting (with or without trickle dusting). In this case, the probability of propagation through the control zone is given by:

$$Pr(Prop) = Pr(Prop)_1)*Pr(Prop)_2$$

Where:

$Pr(Prop)_1$ = Probability of propagation through the first control method, say the explosion barrier, and,

$Pr(Prop)_2$ = Probability of propagation through the second control method, say the trickle stone dusting.

For the combination of campaign stone dusting and explosion barrier used in the examples above, the probability of propagation will be:

$$Pr(Prop) = 0.89*0.35 = 0.31 \text{ or } 31\%$$

The Consequences and Risk of Propagation to Different Positions in a Panel

To be able to complete the risk assessment of the stone dusting and explosion barrier systems installed in a panel it is necessary to assess the probability of propagation to different positions in each panel entry. At each location selected for consideration, the annual frequency of propagation is calculated. At the same positions an assessment must be made of the likely consequences of propagation which when multiplied with the frequency of propagation will yield an annualised risk. The consequences can be expressed in either assets loss (dollars), or fatalities with the risk expressed as cost per annum or fatalities per 100 million working hours, respectively.

Clearly, the further that an explosion propagates the greater the consequence in dollar terms or fatalities. In the event that an explosion propagates to the end of a panel and enters the main development roadways, the likely consequence may be the loss of the whole mine and all those underground at the time.

Application of the Method

By examining the risks at selected points in the panel it is possible to detect deficiencies in the suppression methods applied and to estimate the annualised costs that could be spent to address those deficiencies. High-risk areas will also be clear from this analysis and efforts can be directed in the most effective manner to the reduction of risks to acceptable levels. This requires that for each roadway into a panel there is an assessment of the probability of propagation at selected points with estimates of consequences at corresponding points.

An example of some calculated risks for a typical three heading longwall panel are shown Table 1 which shows the risks at the start of each entry, at a point, say, 600m outbye of the face and at the outbye end of the panel. The data in Table 1 was calculated for illustrative purposes only and no conclusions regarding the effectiveness of any system of dust explosion suppression should be drawn from this table. However, it does show how it would be possible to undertake such an assessment for any panel for the purposes of identifying deficiencies in the explosion control methods. In this case, it is clear that the greatest risk is associated with an explosion propagating along the tailgate into the main headings. Alternative strategies can be assessed at different positions in the tailgate to determine the impact on the risk profile for the panel and the most effective means of reducing this risk. Possible alternative strategies might include increased frequency of campaign stone dusting, improved trickle dusting, and improved barrier design.

Conclusions

A method has been developed that will allow mines to examine the risks associated with coal dust explosions that is sensitive to variations in the suppression techniques employed. This will allow mines to selected the options that minimise the risks involves and maximise the effectiveness of the controls employed. The method is sensitive to parameters such as the dimensions of the panel, the frequency of campaign stone dusting and the rate of trickle dusting.

The authors have presented a quantified method of evaluating the likely effectiveness of explosion protection systems. The input data is a combination of historical fact, mine site experiences and event probabilities drawn from extensive testing. The risk modelling approach is not unduly novel, but the application is.

It is suggested that this type of approach is essential in the new era where mine management need to personally evaluate risk, and judge if they have achieved the duty-of-care based goal of “as low as reasonably achievable”. The authors suggest that with low probability-high consequence events, traditional qualitative risk assessments cannot be used to effectively and impartially judge complex control systems such as those seen in our mines. The method presented is a best practise approach to comparing these complex systems. The final decision on risk tolerability is up to management and regulators, not the authors.

References

(1). Ham, B., Personal Communications
(2) Humphreys, D. R., Stone Dusting Requirements and Options, Report for ACARP Project C8011, July 2000, yet to be published.
(3) Cybulski, W., Coal Dust Explosions and Their Suppression, Translated from Polish by USBM, 1975
(4) Sapko, M., Weiss, E., and Watson, R., Explosibility of Float Coal Dust Distributed Over a Coal Rock Dust Sub-Stratum, Proceedings of the 22nd International Conference of Safety in Mines Research Institutes, Bejing, May 1987.

Table 1 – Illustrative Calculation of a Panel Risk Profile due to Propagation of a Coal Dust Explosion.

Probability of Propagation			
Dust Ignitions Resulting From Gas Ignitions		7.4%	
	Tailgate	Beltroad	Travelling
Enter Roadway	100%	100%	100%
Enter Outbye Zone	48%	17%	48%
Enter Mains	100%	0%	47%
Frequency of Explosions (Events/year)			
Gas Ignitions		2.50E-02	
Dust Explosions		1.85E-03	
	Tailgate	Beltroad	Travelling
Enter Roadway	1.85E-03	1.85E-03	1.85E-03
Enter Outbye Zone	8.88E-04	3.19E-04	8.83E-04
Enter Mains	8.88E-04	0.00E+00	4.16E-04
Consequences (M$/event)			
Face Ignitions		N/A	
Dust Ignitions		N/A	
	Tailgate	Beltroad	Travelling
Enter Roadway	50	100	100
Enter Outbye Zone	60	150	150
Enter Mains	500	500	500
Consequences (Fatalities/event)			
Face Ignitions		N/A	
Dust Ignitions		N/A	
	Tailgate	Beltroad	Travelling
Enter Roadway	2	4	4
Enter Outbye Zone	2	6	6
Enter Mains	20	20	20
Risks (k$/year)			
Face Ignitions		N/A	
Dust Ignitions		N/A	
	Tailgate	Beltroad	Travelling
Enter Roadway	93	185	185
Enter Outbye Zone	53	48	132
Enter Mains	444	0	208
Risks (Fatalities/100 million working hours)			
Underground Employees (total)		80	
Face Ignitions		N/A	
Dust Ignitions		N/A	
	Tailgate	Beltroad	Travelling
Enter Roadway	2.31	4.63	4.63
Enter Outbye Zone	1.11	1.20	3.31
Enter Mains	11.1`0	0.00	5.20