Safety considerations when blasting off the solid in underground fiery coal mines

by G.V.R. Landman* and K.S. Ireland*

Synopsis

In the early days of underground coal mining, the use of explosives to break coal resulted in a large number of disastrous methane and coal dust explosions and consequential loss of life. Research by the British, French, US authorities, amongst others, introduced many practices that significantly reduced the occurrence of such incidences. The use of explosives designed to be safe in a methane atmosphere, plus the creation of a second free face were two such practices which became commonly used in coal mines all over the world including southern Africa.

With its associated coal cutting equipment and labour, the cost of creating a second free face is significant and this, together with the constant drive to reduce mining costs in a competitive market, causes mine management to regularly question the need for the second free face. Also, the safety and nature of permitted explosives has changed considerably since the days of black powder and nitroglycerine-based explosives with the introduction of water-based explosives.

In southern Africa mining regulations pertaining to the blasting of coal has its origins in British research which was largely done in the first half of the twentieth century. More recent research by the US Bureau of Mine has resulted in a deeper understanding of some of the mechanisms of methane ignition by explosives and suggests that some of the earlier regulations can be relaxed to a certain extent without compromising safety.

This paper gives an overview of the original research done in Europe and the more recent work in the USA, to give mine management and regulatory authorities a deeper understanding of the important safety issues when using explosives in a methane atmosphere. It also suggests that blasting off the solid is no less safe than using a second free face providing certain safety procedures are followed.

Introduction

This paper is a summary of a literature survey conducted to investigate the development of safe blasting practice in underground collieries with special reference to blasting off the solid (BOTS). The work was initiated in response to a number of requests to test the practical feasibility of eliminating the coal cutter in the production process by blasting off the solid without the use of the legally prescribed second free face.

The authors aim to provide information to enable mines to better understand the safety risk involved when blasting underground in fiery conditions, and how that risk is influenced when changes in the application of explosives are made, such as changing from a cut face to blasting off the solid. A brief discussion of the origin of undercutting the coalface and the position with BOTS is followed by a more in-depth discussion on ignition theories and the relationship of the mechanisms of the explosive reaction on methane ignition. The paper concludes with an opinion on safety with regard to explosions and ignitions when blasting off the solid and makes suggestions on how South African regulations might be changed in the light of recent research by the US Bureau of Mines.

The practice of undercutting coal

In early handbooks of coal mining, such as 'Coal and Coal Mining' by Sir Warington Smyth[1] in 1890, the getting of coal is described as a breaking down process after a bench, kirve or hole along the bottom of the seam has been cut by pick, two to three feet deep. If gravity did not bring down the coal, heavy hammers were used, or a hole was drilled and fired by gunpowder. The origin of the undercut had therefore more to do with the mechanical advantage that gravity provided than with the safe use of explosives.

Early this century, however, increased awareness of the explosion hazard in collieries resulted in research that proved that an explosion could be started by explosives fired as blown-out shots from a mortar. It was realized that blown-out shots could be brought about when holes were drilled in the solid, or beyond the line of kirving. In the UK undercutting was enforced by law, but in the USA exemptions were given readily for

* *African Explosives Limited, PO Modderfontein, 1645.*

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blasting solid faces in thin seams. Coal mines in India also practice undercutting but allow blasting off the solid provided that special explosives are used. Indian practices are largely based on British regulations. Figure I illustrates the breaking mechanisms of explosives for the two methods of coal blasting.

The main incentive for considering the use of BOTS in recent times is the possible elimination of the coal cutter. The coal cutter has a number of disadvantages including:

- the capital cost of equipment and depreciation
- the cost of cutting picks, changing these and their sharpening
- sparks from the cutting picks striking stone in the coal increases the risk of methane ignition
- the electrical cable is a potential source of danger
- fines generated by coal cutters are often unsaleable and have to be dumped on spoil piles. A 200 mm cut in a 3.0 metre high face represents a loss of 6.7% of the coal blasted where the fines have no value
- coal cutter generated fines have to be cleared away from the face prior to drilling, requiring additional labour or equipment
- coal cutters are often the bottleneck in the production cycle and their elimination can sometimes result in greater productivity.

There are some disadvantages of BOTS including:

- in the UK and India a safer but significantly weaker explosive is required by law resulting in more holes being required and less assurance of full advance
- either angled holes or large diameter centre holes have to be drilled to create an initial opening into which the remaining blastholes can break
- more explosives and initiation components per ton of coal are required
- a larger range of detonator delays is required
- the increased mass of explosives produce larger volumes of post-blast fumes placing greater demands on ventilation requirements.

Figure 1 shows how the breaking mechanism changes when comparing the use of a second free face to blasting off the solid.

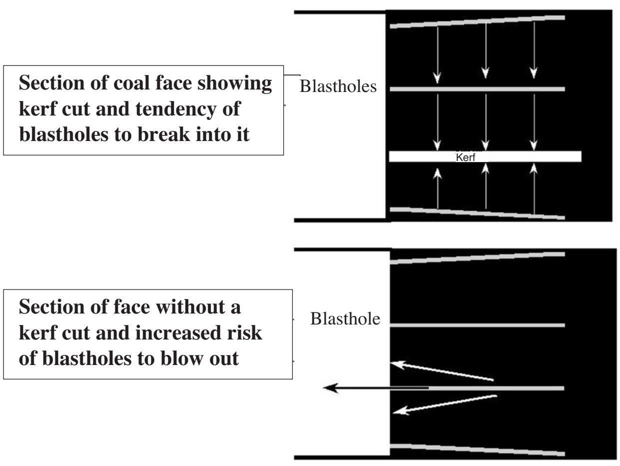

Figure 1—Comparison of kerf cut and solid blasting breaking mechanisms

Blasting off the solid in the UK

Because of the fear of blown out shots when blasting off the solid (discussed later in this paper), the British Safety in Mines Research Board developed a series of tests for explosives to be used in various conditions in fiery conditions. They produced a table of explosives classifications which has been reproduced in Table I. Dr B.J. Thomson[2], Director of the Health and Safety Executive's Explosion and Flame Laboratories, states that BOTS became widespread in the 1960s and 1970s, but has tailed off now that improved heading machines have been developed to replace shot firing in drivages, and since stables in longwalls have been eliminated. The British P4/5 and P5 explosives, required by regulation for BOTS (see Table I), were not designed for power, but rather for absolute safety when used with delay detonators. In experiments conducted in South Africa a few years ago, these explosives proved to be too weak for South African conditions[3].

Blasting off the solid in the USA

Unlike the British, the American system has only one type of *permissible* explosive which is used in all blasting in underground coal mines except where *sheathed* explosives are required. The permissible tests, revised in 1989, are summarized in Table II[4,5]. In the USA BOTS is used in driving headings in narrow seams and for removal of pillars. In various publications from the United States Bureau of Mines (USBM) it is recommended that an additional free face in coal blasting is preferable. The practice of BOTS is referred to in a USBM Information Circular of 1929 (Circular 6147)[6], indicating that it has long been a standard practice in the USA.

There was apparently a popular but mistaken belief that BOTS was looked on with disfavour by the USBM. Dr John N. Murphy[7], a former Research Director of the USBM, has the following opinion:

'The implication that shooting-of-the-solid is less safe than shooting cut coal was, to the best of my knowledge, a widely held belief in the industry and was not based on Bureau of Mines Research'.

In a Report of Investigation (RI 4875)[8] of the USBM, the safety of undercut faces is compared directly with the safety of BOTS. Surprisingly the latter proved to be safer. These results however, cannot be taken as conclusive evidence.

Blasting off the solid in South Africa

The first coal mines in South Africa started producing coal around 1890 and the use of mechanical coal cutters commenced in about 1900, as mentioned in the files of the Government Mining Engineer[9]. Each year since then the percentage of coal produced from 'machined' faces is quoted. By 1940 there were about 500 coal cutters in operation in South Africa, and the percentage of work done to total tonnage mined by collieries using coal cutters was 95%. It can therefore be assumed that in the period prior to 1940 blasting of the solid could well have been practised. The provision of two free faces eventually became legally enforced, as described in Regulation 9.30.3.2. of the Minerals Act.

The renewed interest in BOTS in South Africa raised some questions as to how safe the practice is. There are

Table I

Summary of the British permitted explosives classifications and tests

Group	Application	Tests
P1	Used for instantaneous blasting in undercut coal or relieved rock (rippings) near a coalface, but in British mines with minor exceptions, are principally used for delay blasting in shafts and tunnels away from sources of gas.	1. Twenty-six shots of 142g of explosive, inversely primed and un-stemmed, are fired into a methane/air mixture. Not more than thirteen ignitions may occur. 2. Five shots of 795g directly primed and stemmed, are fired into a methane/air mixture. No ignitions may occur. 3. Five shots of 795g directly primed and stemmed, are fired into a coal dust/air mixture. No ignitions may occur.
P2	These are P1 explosives sheathed by sodium bicarbonate (a flame suppressant). Their use was discontinued many years ago.	
P3	Previously known as 'equivalent to sheathed', the flame suppressant is incorporated in the composition. Used mainly for blasting undercut coal and rock rippings by single shot-firing or instantaneous firing of up to six shots.	1. Twenty-six shots of 397g of explosive, inversely primed and un-stemmed, are fired into a methane/air mixture. Not more than thirteen ignitions may occur. 2. Five shots of 1020g directly primed and stemmed, are fired into a methane/air mixture. No ignitions may occur. 3. Five shots of 567g inversely primed and un-stemmed, are fired into a coal dust/air mixture. No ignitions may occur.
P4	Developed specifically for use in rock rippings with delay firing where there is an inherent possibility of the charge firing into a gas-filled break or parting.	1. Twenty-six shots of 397g of explosive, inversely primed and un-stemmed, are fired into a methane/air mixture. Not more than three ignitions may occur. 2. Five shots of the maximum permitted charge mass are fired into a methane/air mixture using the Break Test 1. No ignitions may occur. 3. Break Test 2 uses a gas mixture of 3.60% propane with air and nitrogen. This mixture is more easily ingited than methane/air. Some test shots are fired and the most hazardous charge not exceeding 227g determined. Twenty-six shots are then fired at this mass and not more than thirteen ignitions may occur. 4. Five shots of 30.5 cm length and 3.7 cm diameter are fired in methane/air in Break Test 2. No ingitions may occur.
P5	Designed for delay blasting in solid coal (i.e. not undercut).	1. Twenty-six shots of 567g of explosive, inversely primed and charged to reach to 5 cm from the mouth of the cannon, are fired into a methane/air mixture. No ignitions may occur. 2. Five shots of 1020g directly primed and stemmed, are fired into a methane/air mixture. No ignitions may occur. 3. Five shots of 567g inversely primed and un-stemmed, are fired into a coal dust/air mixture. No ignitions may occur.
P4/5	Designed to meet both P4 and P5 test conditions	These explosives must pass both the P4 and P5 tests.

Table II

Brief summary of the USA Permissible explosive tests[4] (non-sheathed explosives)

Rate of detonation test Unconfined 0.5 inch (12.5 mm) explosives column is detonated to determine whether an explosive has a tendency to misfire or partially detonate.
Air-gap sensitivity test An explosive is required to propagate across a 3 inch (75 mm) gap between two unconfined cartridges.
Gallery test 1 Explosive is fired from a steel cannon into an 8% natural gas mixture.
Gallery test 2 Explosive is fired into a 4% natural gas mixture in which bituminous coal dust has been predispersed.
Pendulum friction test A small amount of explosives is placed on an anvil and a pendulum released from 59 inches (1.5 metres).
Toxic gases The standard threshold limit (STL) equivalent for each toxic gas is measured by firing a one pound (0.45 kg) charge into a large chamber and analysing the toxic gases produced.

concerns that with only one free face, the likelihood of a blown out shot is increased. Only a thorough understanding of the ignition and explosive processes can help to evaluate this uncertainty.

The theory of ignition

Ignition mechanisms as they developed over time are reviewed.

The French doctrine of 1890

According to Coward[10], gunpowder was the only practical blasting explosive in collieries around the world until 1880. The regular occurrence of ignitions and explosions in collieries in the late eighteen hundreds and early nineteen hundreds helped to focus attention on the explosion problem and the role blasting in collieries played in its inducement. Gunpowder was recognized as an explosive which deflagrates if unconfined. This behaviour produced a large reactive flame of burning constituents outside the shothole which were exceedingly incendive and therefore dangerous in the presence of methane.

Mallard and Le Chatelier (reported by Coward[10]) observed in 1888, that the temperature and duration of exposure to the ignition source were two critical conditions that governed the ignition of methane. These experiments were conducted by passing methane through preheated tubes. They also observed an ignition delay period which varied from one to ten seconds for initiation temperatures just above the minimum ignition temperature, i.e. between 600°C and 800°C. Higher initiation temperatures caused a decrease in the ignition delay period which became inappreciable above 1000°C. Naylor and Wheeler[11] did more precise measurements of the lag on ignition of firedamp in 1925, but confirmed largely the observations of Mallard and Le Chatelier.

Coward[10] further reports that Mallard and Le Chatelier, in a report to the Commision des Substances Explosives in 1888, pointed out that for explosives to be safe the flame temperature outside the hole should be maintained below the ignition temperature of methane. Although it was realised that no explosive detonates at such low temperatures, they argued that the gaseous products of detonation of a solid high explosive can expand so rapidly that they cool before ignition of the methane can take place. Table III provides temperatures calculated by them for explosives gases expanding one thousand-fold. Clearly the incendivity of the products is much reduced by their rapid expansion.

In addition, a dynamite charge was confined in a steel tube in such a way that one third of the energy released by the charge was used to burst the tube, leaving the unexpanded gas at a temperature of 2200°C which, after expansion has taken place, will fall to well below the ignition temperature of methane. This led to the 'French doctrine of 1890', an official decree that stated that explosives used in coal should have a detonation temperature below 1500°C.

To obtain 'cool' explosives, explosive manufacturers used mostly ammonium nitrate with nitroglycerine, or other nitrate hydrocarbons as sensitizers. Cooling salts and cooling agents were also introduced to reduce the temperature of the flame. The French doctrine led to improved safety during shot firing in collieries, but did not eliminate the problem as was confirmed by ignitions that were still taking place. It was soon realized that the conditions of firing affect the mechanism of ignition. A more complex explanation of the ignition mechanism was required. Possible causes of ignition were formulated by a variety of researchers building on the understanding that was provided by the 'French doctrine'.

Mechanisms of ignition of methane by explosives

The influence of firing conditions on the incendivity of explosives was illustrated by Taffanel and Dautriche (as reported by Coward[10]) in experiments where the same explosive was exploded:

- in a closed bomb
- in an open ended cannon without stemming
- freely exposed in a large vessel.

They observed that 30% less heat in the cannon shot and 60% less heat from the freely suspended shot occurred, implying increased energy transfer to the combustible environment surrounding the shot. Energy transfer could occur by compression, mixing, conduction or radiation, all influenced by the condition or circumstance in which the shot is set off.

In 1922, Lemaire (reported by Coward[10]), in Belgium, listed the following possible causes of ignition of methane by explosives:

- Detonation flame wave
- Product flames before mixing with the surrounding atmosphere
- Flame when products meet the atmosphere
- Hot product gases
- Projected solid particles of unburnt explosives
- Compression due to shock waves.

He noticed that explosives with high charge limits gave small flames, but understood that flame size was not a criterion of safety. All the phenomena he listed he considered interrelated and resulted in a complex matrix for ignition conditions.

In 1927 Payman[12] succeeded in obtaining a clearer understanding of how the different explosive phenomena interact to affect ignition of methane. He concentrated on the effects of methods of firing on the safety of explosives used underground, in order to help the shot firer to use them safely, instead of effects of materials used in the manufacturing of explosives in order to try to make them inherently safe. He separated observation of the different phenomena by use of photography of flame and the shock wave over time at the mouth of a steel mortar. He illustrated that cooling salts enhance the brightness and actinic value of the flame. Flame volume, as such, is therefore not an indication of its danger.

With this method he indicated how shock wave, flame and expanding gases are influenced when the hole is primed in different positions, in different geometries and with or without tamping. Four years later Grimshaw and Payman[13] proposed an ignition mechanism based on Payman's work. In 1937 Payman and Wheeler[14] developed this further and divided the causes of ignition into four groups, namely:

- Flame
- Gaseous products of detonation
- Compression of the firedamp-air mixture
- Hot solid particles.

Each of these causes is discussed below.

Flame

Three flames could be distinguished.

The detonation flame is the flame, which travels from one end of a cartridge to the other as it detonates. The flame is produced by the chemical reactions, which transform the solid explosive into gas at high pressure and capable of doing work. Complete decomposition may not take place in the detonation flame so that the maximum temperature is actually attained behind the flame-front. This flame is extremely incendive for methane and should be contained.

Luminous solid particles, which appear to be a flame projected from the explosive. These luminous particles are hot, chemically reactive and therefore able to ignite methane. However, they are usually surrounded by gaseous products of combustion, which are mainly non-flammable and non-supportive of combustion. Therefore, as long as they do not break through the gaseous products, ignition will not take place.

Table III

Detonation and gaseous product temperatures of two explosives (Mallard and Le Chatelier as reported by Coward[10])

Explosive	Detonation temperature (°C)	Temperature after gas expansion (°C)
Nitroglycerine	3 170	978
40/60 guncotton/AN	2 450	502

A secondary flame, or a luminous haze, which forms due to over-oxidization of permitted explosive. Excess carbon and hydrogen are further reduced, and the exothermicity of the reaction causes heat to build up and this can be observed as glowing gas, which is not very incendive.

Gaseous products of detonation

These gases were found to contain little oxygen and therefore they tend to have an extinguishing effect on any flame with which they mix. They are however, very hot initially.

Compression

Payman and Wheeler[14] also reported that in adiabatic compression, a 9% methane-air mixture ignites at a temperature as low as 450°C. This was accomplished when the mixture was compressed by a piston in a steel cylinder to one thirteenth of its original volume. Since temperature increases with compression, the final pressure is 32 times the initial pressure. As the gaseous products of detonation from an explosive may travel outwards at 3000 m/s or more, adiabatic compression can be assumed to occur and can therefore cause ignition of methane.

Hot solid particles

Records of Schlieren photographs showed that a separate mass of apparently non-luminous particles are formed, intimately associated with the gaseous products, but travelling mainly in advance of these gases and may penetrate and even travel in advance of the main shock-wave. It is doubtful if these particles are able to ignite methane.

Figure 2 illustrates the phenomenon as observed and discussed by Payman and Wheeler[14].

The US Bureau of Mines also investigated possible ignition mechanisms. In 1954 Grant and Mason[15] published a series of Schlieren photographs illustrating the ignition process if explosives are allowed to eject from a small mortar into a flammable environment.

Their conclusions are very similar to those of Payman and Wheeler[14]. The mechanisms by which explosives can cause ignition of a methane/air mixture are:

- ➤ Ignition directly by flame or hot gas
- ➤ Ignition by solid particles of the reacting explosive, either at the cartridge or thrown out by the explosion
- ➤ Ignition by compression.

Figure 3 shows the development of shock wave and gaseous products of detonation when an un-stemmed charge is fired. In Figure 3(a) one notices a curved detonation front of the explosive charge. When this front breaks through at the end of the charge as shown in Figure 3(b), the centre leads the wave at the rim. An orifice may form through which a portion of gaseous products rushes to form a hot jet of detonating substance. The jet will be penetrating into the flammable atmosphere while at a temperature of about 3500°C. Meanwhile the gaseous products from the earlier phase of the detonation, just behind the jet, has burnt itself out expanding in the borehole and have as a consequence been cooled considerably. These gases will surround the hot jet with a cold medium, leaving no time for adequate heat transfer or quenching of any initial ignition that started to take place.

Ignition or non-ignition therefore depends primarily on the formation of a jet and the subsequent effect of cooler gases on further heat transfer. For non-permitted chemical explosive formulations, the jet temperatures are so hot that ignition is almost immediate and the jet discharges so rapidly that the cooler gases cannot encircle it.

Grant and Mason[15] therefore reduced the list of phenomena leading to ignition of methane to flame, pressure and hot particles.

Flame

Flame can be either the flame of detonation making contact with the atmosphere through the ejecting jet of reacting explosives as explained above, or it can be the last portion of solid explosives which forms the nozzle or orifice and which do not react. These might react when expelled ahead of the chemical reaction and react with oxygen when in contact with

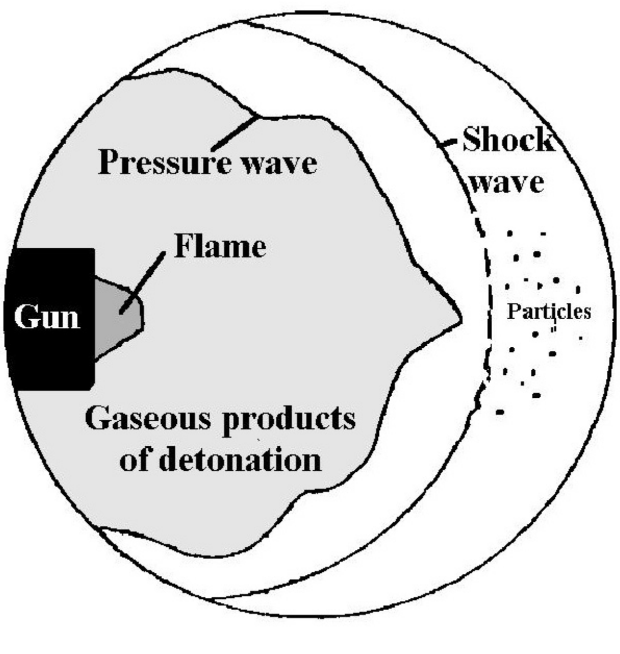

Figure 2—Shock-wave, gaseous products of detonation and flame at the mouth of a mortar, Payman and Wheeler[14]

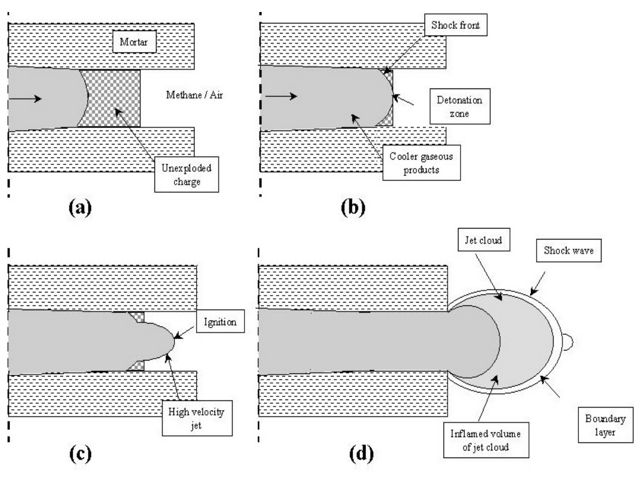

Figure 3—Development of shock wave gaseous products of detonation when an un-stemmed charge of tetryl is fired from a borehole into a flammable atmosphere, after Grant and Mason[15]

a flammable environment. Flame can also develop if the reaction in the gaseous products is incomplete. With modern explosives, the reaction is mostly complete and cooled by additives of salts to such an extent that all further development of chemical activity is not taking place. For example, according to Urbanski[16], flame duration is reduced from 8 ms for a nitroglycerine-based explosive to 0.5 ms for an ammonium nitrate mixture. Flame temperature in the detonation wave for ammonium nitrate is of the order of 1770°C with a detonation velocity of 3460 m/s, compared to 5730°C and 8060 m/s (never actually achieved) for nitroglycerine, as calculated from the hydrodynamic theory of detonation—Coward[10]. Only a rough correlation between velocity of detonation and incendivity of an explosive exists.

Pressure

Some explosives, when used in large quantities, ignite methane by compression and therefore a charge limit is often set. This ensures that all the energy of the charge is transformed into work, preventing a shock wave from adiabatically compressing a methane-air mixture, forcing the mixture to ignite. As the shock wave travels through the hot gaseous products, ignition might occur, but ignition might also start in spots not yet reached by the flame of detonation, since the shock wave velocity is higher. Fordham[17] also mentions that the indirect action of the shock wave, after it has been reflected from a solid surface, can act as source of ignition.

It was found that a mixture of 6.5% methane with air might ignite when subjected to rapid compression to a pressure of 5.5 MPa by mechanical means as reported by Urbanski[16]. Although the adiabatic equations of state for the vapour of a compressible substance are applicable here for the gaseous ignition by compression $T_2/T_1 \approx (V_1/V_2)^{\nu-1}$, a more complex mechanism for shock wave ignition of dust is given by Sichel *et al.*[18]. As the shock wave passes over the dust particle, supersonic flow around the particle is induced, and convective heating causes a rapid temperature increase of the particle surface. The drag forces accelerate the particle, reducing the relative velocity of particle in relation to the hot gaseous environment. The rate at which the particle and the gaseous oxidizer react increases until the critical temperature is reached and a runaway reaction starts.

Hot particles

Regarding solid particles, care has to be taken with selection of wrapping materials and closure clips. The wrapping materials and cartridge closure clips can heat up during the detonation process to temperatures that might induce ignition when in contact with a flammable atmosphere.

Other parameters

Finally, Landman[19] indicated that the geometry of the source of ignition in a combustible environment also influences the chance of an ignition taking place. He indicated that the smaller the source of ignition, the higher the temperature required to effect ignition. On the other hand, the more spatially extended the source of ignition, the more readily heat transfer takes place making the environment more susceptible to ignition. When a detonating explosive is considered, the geometry of the conditions surrounding it influences the ultimate shape and size of the jet of hot gases that will be ejected. Also, the initial physical condition of the rock or coal can influence the development of the detonation reaction and, as a consequence, the chemical behaviour of the explosive substance under varying geometrical conditions can be different with different ignition properties.

Flame and incendivity

The physical conditions in which an explosive reaction takes place dictate the subsequent reaction behaviour that can be expected from the chemical composition involved. Three physical conditions are considered to be of particular danger with regard to initiation of a flammable atmosphere. They are:

- Blown out shots due to inadequate or omitted stemming
- Partly confined or totally exposed shots
- Premature venting into breaks or discontinuities.

Coward[10] discusses the changing nature of the same explosives in different conditions, and he cites work of Ahrens, Taylor and others. A short explanation of the selective and inconstant nature of the explosive reactions under different environmental conditions follows

Propagation of the detonation wave through the explosive is regarded as 'selective' because reactions are still occurring after the detonation wave has passed. Propagation is only controlled by reactions that can take place sufficiently quickly under the influence of the shock wave. The slower reactions occur behind the detonation wave and are regarded as very incendive. These retarded reactions may be incomplete at the time of pressure release, yet able to recommence actively if external conditions allow. With blown out shots, breaks in the face and exposed charges, such secondary chemical reactions might be difficult to control. In addition, explosives with inadequate oxygen content leave combustible substances in their products and these can easily ignite and in turn ignite a methane atmosphere.

The only way to reduce the incendivity of the exploding substance under these conditions is either to allow for sufficiently rapid expansion to 'freeze' the reactions or to provide adequate confinement to ensure that the secondary reactions are completed before the primary products escape. In compositions of modern coal mine explosives, the chemical compounds are adjusted so that they contain enough oxygen to burn all the carbon and hydrogen that might be present, but making sure that minimal surplus oxygen is present to cause the production of the highly toxic nitrous fumes. The addition of salts to reduce flame temperature, and in some instances ion exchange, are additional factors used to reduce and limit the extent of secondary incendive reactions. In the nineteen fifties, selectivity of asphyxive physical reactions were studied in detail in an attempt to find incendive asphyxive compounds.

For example, Ahrens studied the selectivity of chemical reactions under shock in order to obtain understanding of the incendive potential of different explosive compositions. He observed that the slower reactions, which can occur later among the detonation products, are potent agents of methane ignition. These secondary reactions may be incomplete at the time of pressure release, but capable of commencing later under some external conditions, such as deflection.

Figure 4 illustrates ignition due to secondary uncontrolled reactions formed by early venting in the course of detonation. These secondary reactions can be shut down or 'frozen' by sudden pressure release. Adequate confinement allows the retarded reactions to be completed when pressure release occurs and these slower reactions will contribute to the power of the explosive as long as the charge is confined in the shothole, but since no work is done on release, the energy is transferred to the surrounding atmosphere.

Between these two safe situations of rapid release and proper confinement, an intermediate unsafe one exists in which the secondary reactions are incomplete after the expansion, resulting in flames hot enough to ignite methane. These incendive reactions are carried into the methane/air mixture. Since confinement can be imperfect, explosive constituents are chosen to suppress the heat of the secondary reactions during expansion. Alkaline metal salts such as sodium and potassium chloride are the most effective chemicals used in achieving this heat suppression.

Operational conditions

Provision of a second free face during driving of a heading does undoubtedly contribute towards more efficient use of explosives. Usually fragmentation is found to be more uniform, although the point is debatable since a lot of fines are produced during the cutting operation.

Establishing the cut is accompanied by its own problems. Four dangerous situations, which might lead to early airing of the detonation process, are illustrated in Figure 5. The first diagram, Figure 5(a), shows a vertical break parallel to the face and ahead of it. With a 2.8 m cut in place, blastholes might intersect the break connecting it with the cut. The second diagram, Figure 5(b), shows a face that has sagged in the middle, causing strata separation which again might be intersected by a blasthole. In earlier times the cut would have been supported with a wooden sprag soon after the cut was finished, but this practice has fallen into disuse in recent times. The third diagram, Figure (5c), shows a loose block of coal, which can provide cracks through which early pressure release into the cut can take place. Finally, an inaccurately positioned blasthole with a totally inadequate toe burden is illustrated in Figure 5(d). Early release into the cut can therefore easily follow. Each of these situations demonstrates that the second free face might help breaking, but does not necessarily reduce the release of hot gases into a methane atmosphere.

In addition, the files of the Government Mining Engineer[9] show that up until 1994, fifty-six casualties connected to machine mining (= coal cutting) occurred, of which 3 were fatalities. The mere presence of the coal cutter in a confined space, the cutting operation in a slot which produces high dust counts, electric apparatus and cutter positioning right at the newly exposed face are aspects that contribute to the increased risk of injury when a coal cutter is present.

Figure 6 shows a blasthole driven into a solid face, but intersecting a vertical break ahead and parallel to the face. Although early release of the explosive pressure is possible, entry into a gaseous environment of the retarded detonation

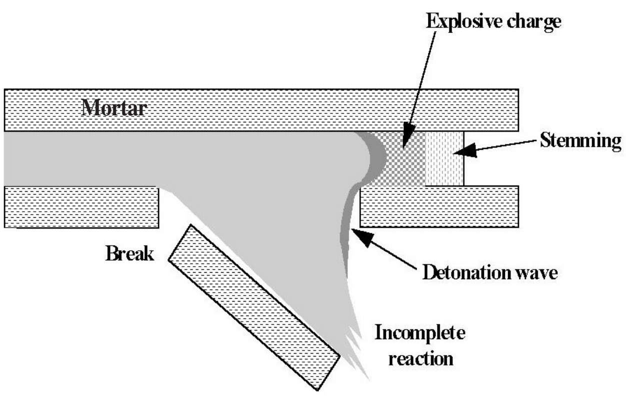

Figure 4—Ignition due to secondary uncontrolled reactions formed by early venting in the course of detonation

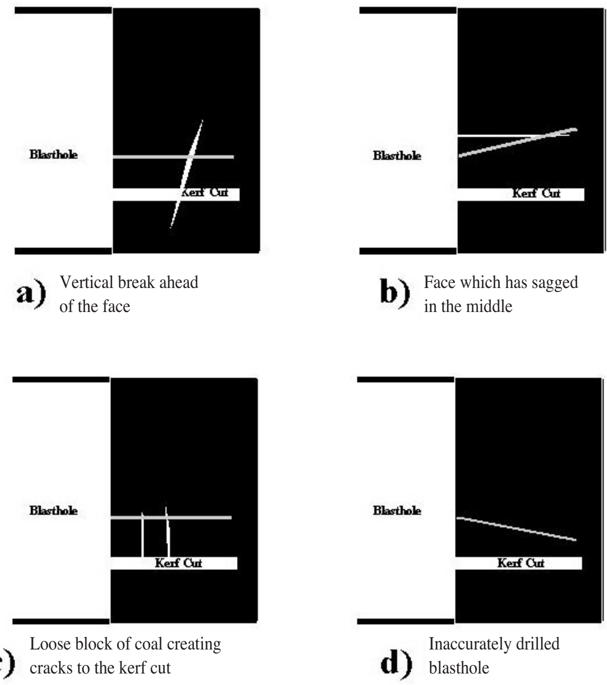

Figure 5—Operational conditions that might develop in a cut face in relation to the geometric position of blastholes, breaks and cracks

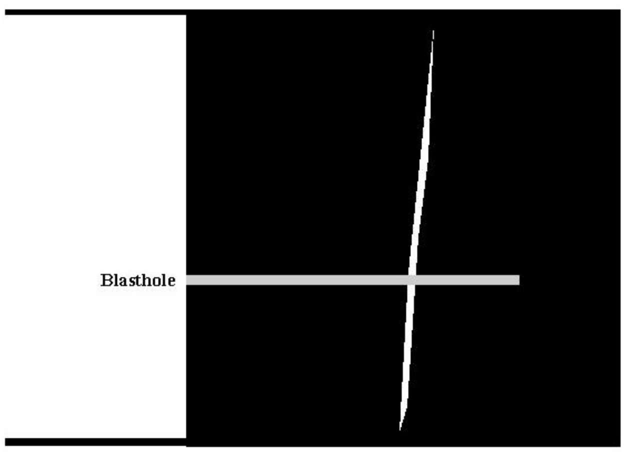

Figure 6—Blasthole position in relation to a coal break in a solid face

reactions is unlikely. In this respect, BOTS is safer than a face with a cut present. From the foregoing explanations, it is therefore not surprising that Nagy *et al.*[8] found faces blasted off the solid to produce fewer ignitions than faces with cuts. They describe an experiment where a coal heading was sealed by a diaphragm and filled with a 9% methane/air mixture. Shotholes 50 to 75 mm in diameter were drilled 1.65 m deep. Delay detonators were used with 25 ms delays, resulting in interval time spans of up to 125 ms. A variety of blasting variables were monitored, but regarding comparison of undercut and solid coalfaces these were the conclusions:

In 26 tests in undercut coal, 19 ignitions were produced, and in 16 comparable tests in solid coal, 6 ignitions were obtained. The result is surprising and contrary to the commonly accepted notion that 'shooting-off-the-solid' is more hazardous from the stand-point of explosion probability, because blown-out shots are more probable in solid faces.

In their regulations for explosives used in coal mines, the US Mine Safety and Health Administration[4] (MSHA) stipulated that prior permission must be obtained if more than twenty holes are to be fired in a single blast. Recent discussions with the authors of this paper have established that there was no scientific basis for this restriction, which did not apply to the vast majority of underground coal mining operations in the USA due to their narrow coal seams and relatively small headings. Also, the shot exploders available at that time were only capable of firing a maximum of twenty detonators. So the limit of twenty holes per blast was not deemed onerous and could be applied until such time that the safety implications (if any) of firing more than twenty holes per blast could be investigated.

Delay blasting in coalfaces

In the late nineteen forties, the demand for increased rate of coal production, changes in mining method and introduction of new machinery resulted in modified or new blasting practices. Hartmann and Lewis[20] report that the USBM did an extensive study to determine conditions under which the charge limit could be increased in the presence of a combustible environment. The charge limit was increased from 680g (1.5 pounds) to 1360g (3 pounds). Further efforts to increase production rates led to the practice of simultaneous charging, followed by separate firing without inspection for gas after each shot. To eliminate this danger, an electric short period delay detonator was designed with inter-hole delays of 25 to 50 milliseconds. Since many States in the USA prohibited any form of multiple short delay blasting, Hartman and Lewis tested delay times in actual coalfaces in the presence of methane.

A total of 264 large-scale experiments were conducted in a Pittsburgh coal seam, of which 163 were short-delay multiple blast tests. The seam was 1.6 m high, face width varied between 2.75 m and 6.4 m, burden was generally 0.61 m and charge per hole varied between 160g and 1500g. The delay times between successive shots ranged from 10 to 125 milliseconds. Their findings included the following:

- For equal charge mass per shot hole, short delay multiple firing never produced ignitions when stemming was used, even with as little as 25 mm (one inch) of stemming
- The firing delay had little effect on ignition probability for un-stemmed holes
- Larger drill holes and larger diameter cartridges produced ignitions more readily in un-stemmed holes than smaller diameters
- Blasting in undercut faces produced gas ignitions more readily than blasting in solid faces.

Nagy *et al.*[21], in similar experiments, used inter-hole delay times between 25 milliseconds and 5800 milliseconds. In combined suspended-niche shots, a charge was placed in a niche in the face, and another freely suspended charge was placed 0.3 m, 0.45 m and 0.9 m away from this niche charge. In some experiments, the free charge was encased in coal dust. The freely suspended charge was ignited first, investigating potential incendivity of cut-off situations. In the full-face experiments, burdens were also changed. Figure 7 illustrates their experimental set-up.

Gas could not be ignited by a cut-off charge of permissible explosives when the firing delay interval was less than 5400 milliseconds, or by a non-permissible explosive when the delay was less than 840 milliseconds. Their experiments indicated that the ignition frequency increases as the delay interval increases from 930 to 5500 milliseconds. They also concluded that the ignition frequency decreased as the estimated burden was increased. In 25 experiments made with burdens ranging from 0.1 m to 0.6 m, only two ignitions occurred. Coal burdens below 0.15 m were found particularly dangerous.

Mainiero and Verakis[22], in a much later experiment (in 1986), conducted similar research to determine whether the total elapsed delay time for blasting bituminous coal in underground mines could be safely expanded beyond 500 ms (in the USA) to 1000 ms. The increase to 1000 ms was found to have no detectable effect on safety relative to incendivity, as long as permissible practices were observed in all aspects.

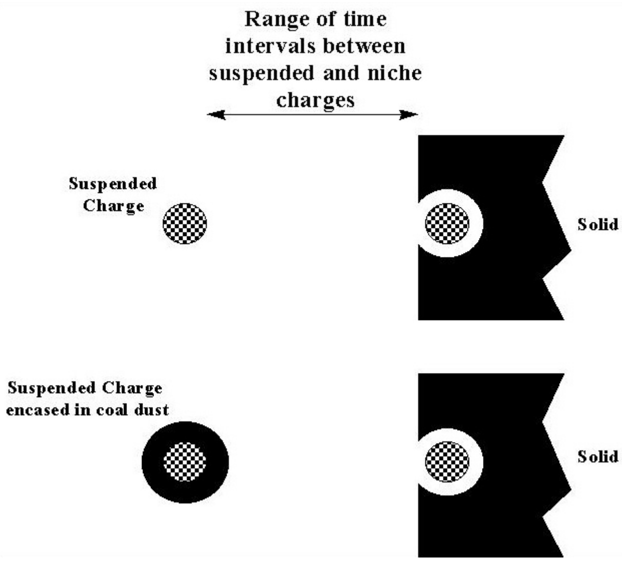

Figure 7—Combined suspended-niche shots, according to Nagy *et al.*[22]

Conclusions

Research done since the adoption of British practice in southern Africa would suggest that these are more restrictive than necessary for modern mining conditions and safer modern explosives. The consideration of less restrictive practices is worth investigation. Based on the research work discussed in this paper, the following practices are considered to be safe by the USBM *providing permissible practices are observed.*

- A charge mass per blasthole of up to a maximum of 1360 g.
- Cartridge containing the detonator must always be the first cartridge placed in the hole (i.e. toe priming and not mid or collar priming).
- Only pliable clay cartridges to be used for stemming and not 'water stemming bags' when blasting off the solid. The use of recently developed pumpable stemming has been tested in South Africa and found to pass the gallery tests.
- A maximum nominal delay of 1000 ms using approved detonators designed for fiery mines.
- When blasting off the solid, nominal delays between adjacent shots must be a minimum of 50 ms and maximum 100 ms.
- A minimum distance between blastholes and a free face, or to adjacent blastholes, of 0.6 metres.

Permissible practices in South Africa would include:

- Only SABS approved explosives to be used
- Only SABS approved delay detonators and shot exploders to be used
- Approved stemming must be used
- Tests for methane to be done in the blast area prior to every blast
- Coal dust suppression standards rigorously complied with.

Whenever mining is undertaken, increased risk cannot be tolerated. Considering the evidence as extracted from previous research world-wide, the authors are of the opinion that the explosion safety risk is not adversely influenced when replacing the undercut with BOTS, provided that permitted blasting practices are rigorously adhered to.

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