Application of protection means against explosions in underground mines

L. Medic Pejic·[1]; J. García Torrent [1,2]; E. Querol Aragón [1]; L. Montenegro Mateos[1]

[1] Departamento de Ingeniería Química y Combustibles, Universidad Politécnica de Madrid, C/ Alenza 4, 28003 Madrid, Spain.

[2] Laboratorio Oficial J.M. Madariaga, C/ Eric Kandel, 1 - (TECNOGETAFE). Parque Científico y Tecnológico de la UPM. 28906 Getafe (Madrid)

Abstract- Underground coal mines explosions generally arise from the inflammation of a methane/air mixture. This explosion can also generate a subsequent coal dust explosion. Traditionally such explosions have being fought eliminating one or several of the factors needed by the explosion to take place. Although several preventive measures are taken to prevent explosions, other measures should be considered to reduce the effects or even to extinguish the flame front. Unlike other protection methods that remove one or two of the explosion triangle elements, namely; the ignition source, the oxidizing agent and the fuel, explosion barriers removes all of them: reduces the quantity of coal in suspension, cools the flame front and the steam generated by vaporization removes the oxygen present in the flame.

The present paper is essentially based on the comprehensive state-of–the-art of Protective Systems in underground coal mines, and particularly on the application of Explosion Barriers to improve safety level in Spanish coal mining industry.

After an exhaustive study of series EN 14591 standards covering explosion prevention and protection in underground mines, authors have proven explosion barriers effectiveness in underground galleries by Full Scale Tests performed in Polish Barbara experimental mine, showing that the barriers can reduce the effects of methane and/or flammable coal dust explosions to a satisfactory safety level.

Keywords: Prevention and protection in underground mines, Passive water barriers, Spanish coal mines, coal dust explosion.

1. Introducción

More than 100 years have passed from Courrières mine disaster in Northern France which killed 1,099 miners in 1906 or in the worst mine explosion at Benxihu Colliery, China, which killed 1,549 in 1942 [1]. What had changed since that time, after a big effort in recognizing and implementing a prevention and protection means into mine practice? Answer is simple; such big catastrophes are very unlikely but even at the end of the 20th century whole mines with the whole crew were canceled by the coal dust explosions. Examples: June 1, 1988: underground brown coal mine Stolzenbach in Federal Republic of Germany, 53 fatalities, August 27, 1990: underground lignite coal mine Dobrnja in Bosnia and Herzegovina, 180 fatalities, nobody survived, May 9, 1992: underground hard coal mine Westray in Nova Scotia (Canada), 26 fatalities, nobody survived.

Causes of such impressing disasters are extremely simple: ignoring of elementary protective means and regulations. Such a statement is related to the coal dust explosion protection, not to methane one. First of all, the presence of coal dust layers in the workings is clearly visible, advanced monitoring instruments are required to control the methane content in mine air. Secondly, ignition energy of methane is extremely small (minimum ignition energy is 0.28mJ), for coal dust it is at least 100 times greater. So, the number of methane explosions is much greater than coal dust ones. In the US coal mining industry, on the most safest in the world , in years 1980 – 2006 it was 15 methane explosions with 106 fatalities , and 2 coal dust explosions with 15 fatalities only. It is very likely that at least part of the explosions recognized as methane ones were transformed into coal dust explosions.

2. A BRIEF DESCRIPTION OF A COAL DUST EXPLOSION

A coal dust explosion travelling along a roadway can be divided into several zones [2]:

- Ahead of the blast the air is still.
- As the explosion develops, the front of the blast becomes a ‘shock wave’, similar to a nearby thunderclap or a supersonic ‘boom’ from an aircraft. It travels faster than sound, so it is not possible to hear it coming. The speed of the shock wave begins at about 360m/s for the weakest explosions up to 700m/s for fairly strong ones. In more familiar terms, these speeds are 1,300km/h to 2,500km/h. They can be even higher for extremely strong explosions.
- The region behind the shock wave, ahead of the flame, experiences a cyclone-force wind. The air is thick with dust which has been scoured from every surface in the roadway. The dust concentration makes the air literally choking to breathe.

  Wind speeds range from 30m/s to 450m/s (108km/h to 1,600km/h) for weak to fairly strong explosions. At these wind speeds nothing is safe. Heavy equipment is overturned, wheeled equipment moves, spiral ventilation ducting unravels into ribbons of sheet metal, and anything loose becomes a missile. And it is all in the dark because of the thick dust. The distance between the shock wave and the flame front increases as the explosion travels further, since the shock wave travels considerably faster than the flame.

- The flame travels at a speed slightly greater than the wind, but slower than the shock wave. (This means it travels in the dust-laden air, rather than in its own combustion products.) Speeds would range from just over 30m/s to 530m/s (120km/h to 1,900km/h) for weak to fairly strong explosions.
- Behind the flame the air is relatively still, but very hot. Shortly it will begin to cool and contract, tending to draw gas back. This will cause less violent movements back towards the point of origin of the explosion, followed by a series of decreasing oscillations

3. PROTECTIVE MEANS

The Couriers disaster showed the dominating role of coal dust in the mining explosion in the presence of the firedamp, even though as an explosion factor, it is not necessary for coal dust explosion to occur. To answer the above questions the simple, general model of an explosion of any flammable substance is very useful. This model relates to all explosion phenomena with combustion, not only in underground mining. Appearance of explosion requires the simultaneous appearance of five factors, forming the so- called explosion pentagon. [3].

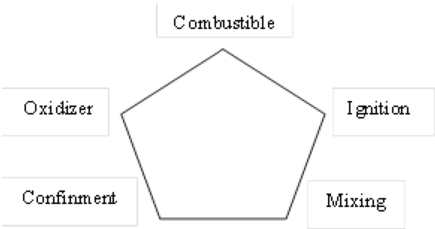

Fig.1 Explosion pentagon

Lack of one of the elements of the pentagon or braking connection between them excludes the explosion's appearance. In the case of the underground coal mine this model says that:

- Combustibles: coal dust and methane. Coal dust exists by its nature and participates in the explosion; methane plays also considerable role but rather as a primary explosion or as a constituent of hybrid mixtures.
- Oxidizer is atmospheric air.
- Ignition sources results from mining technology.
- Underground mine workings are by their nature confined rooms where overpressure can grow, without dissipating as it otherwise would in open space.
- Mixing of combustible and oxidizer or the forming of the dust cloud in air occurs in coincidence with ignition. In a normal state the dust cloud is not in explosion concentration range for the mine air; the presence of people in such a cloud of dust is not possible.

PRIMARY EXPLOSION PROTECTION

Primary explosion protection purposes at substituting something else for the flammable substances or the atmospheric oxygen or reducing their quantities to the point where there is no danger of an explosive mixture forming. Increased air circulation, air flushing through ventilation can be achieved by structural measures. Replacing the atmospheric oxygen is not an option for areas where people work.
Much research has been carried out in Europe and elsewhere to understand how to control these dangers, but explosions still occur. In the coal mining industry, a methane explosion can initiate a coal dust explosion, which can then engulf an entire pit working. Stone dust is spread along mine roadways, or suspended from trays in the roof, so as to dilute the coal dust raised ahead of the combustion zone by the shock wave, to the point where it cannot burn. Mines may also be sprayed with water to inhibit ignition.
Good housekeeping practices, namely eliminating the build-up of deposits of coal dust that may be disturbed and lead to a secondary explosion, also help mitigating the problem.
For this reason the measures available for such locations are limited to:

- Avoidance or restriction of substances which are capable of forming an explosive atmosphere.
- Avoidance or restriction of release of the flammable substances and therefore formation of explosive mixtures.

SECONDARY EXPLOSION PROTECTION

Action directed at secondary explosion protection aims to prevent sources of ignition. The hazard of combustion can originate from electrical and mechanical equipment, or even from persons. In practice, secondary explosion protection is implemented by technical action and organizational action. Organizational action may take the form of instructing the workforce and having plant and equipment cleaned properly.

TERTIARY EXPLOSION PROTECTION

Action directed at tertiary explosion protection aims to negate the harmful effects of explosions and thus minimize the risks to the health of workers.
Such action could be:

- Explosion pressure-resistant design
- Passive and active explosion barriers
- Automatic extinguisher systems
- Organizing escape routes

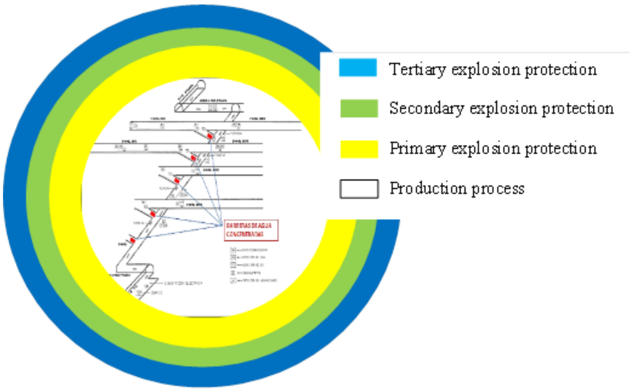

Fig. 2. Protection steps in coal mines

II. PASSIVE AND ACTIVE EXPLOSION BARRIERS

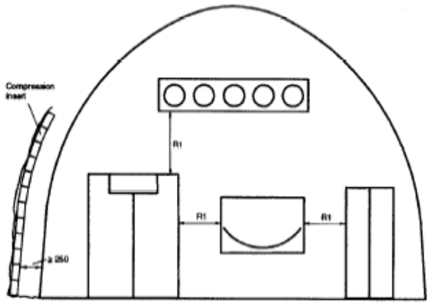

Fig. 3. Ventilation doors

The aim of the protection measurements is to prevent, once explosion had started, this one will become increasingly important when propagating. It should be pointed out that secondary explosions of coal dust that happen after the primary ignition are really devastating, since they imply very big quantities of combustible matter, they generate devastating energies and are capable of propagating along kilometers of galleries. It is obvious that an explosion can be stopped as soon as possible, there are fewer consequences resulting.

I. 2-BAR EXPLOSION PROOF VENTILATION STRUCTURE

The standard UNE-EN 14591-1:2005 [4] Explosion prevention and protection in underground mines - Protective systems - Part 1: 2-bar explosion proof ventilation structure defines the characteristics of the ventilation structures (air locking box and ventilation doors) that must provide an apropriate ventilation flow in case an explosion occurrence, to limit the effects of the explosion in the ventilation systems and to preserve escape and rescue possibilities.
This Explosion proof ventilation structure is capable to resist explosion overpressure up to 2 bar that implies at least an air locking box, that cuts the roadway section leaving an opening for transport, passage of personnel , conveyor belts, pipelines and cables, as well as necessary openings to assure necessary ventilation airflow.
The materials and components used for ventilation doors must be non-combustible and approved for use in underground mining, according to the dimensions defined in the standard. They must be embedded in the gables with a minimum depth of 250 mm in all its perimeter. Ventilation doors can be for passage of personnel or transport and must withstand a pressure of 2 bar. Two types of doors maust be distinguished: pressure relief vent doors (those whose leaves are opened and closed in opposite directions) and non pressure relief doors (normally open against the direction of air flow with mechanical devices for opening and closing). Figure 3 depicts ventilation doors for personal and protective transport.

II. PASSIVE AND ACTIVE EXPLOSION BARRIERS

An explosion should be confined to the area in which it is initiated. The alternative to this approach is to attempt to protect the entire mine.
The protection would need to be adequate for well-developed explosions; incombustible levels of at least 85% would be required throughout the mine. This is believed to be impractical. The better approach is to concentrate suppression measures close to the likely points of initiation.
It will be apparent from the comments about stonedusting that, while stonedusting is a very effective way of suppressing explosions, there may be circumstances in which it is not totally effective. Two obvious instances of this are:
- roadways in which a conveyor belt is installed, where the coal on the belt and the dust generated by movement and transfer cannot be protected by stonedusting; and
- return roadways, where failure of a trickle duster may allow coal dust generated by mining to form a layer on top of stonedust.

In both situations additional protection is required as a backup, to make certain that an explosion will not propagate to the rest of the mine. At present, this protection should be provided by passive barriers.
There may be other situations which produce likely points of initiation of an explosion. These places should be assessed to determine whether adequate protection is provided by stonedusting alone. If not, these should also be obtained by additional protection by barriers.
Explosion barriers (EN 14591-2) [5] are the essential part of the explosion protection system (see Figure 4) in underground coal mines, being one of the so called layers of protection.
A passive barrier relies on the fact that the wind blast from an explosion travels ahead of the flame. The energy in the wind blast is used to disperse an extinguishing agent -usually water or stonedust - into the air in the path of the oncoming flame, so that the flame will be extinguished.
Barriers are rather far protection layer acting in case of failing nearer layers. Explosion barriers are divided into two groups depending on the extinguishing agent used:

- Stone dust barriers, where incombustible dust (mainly calcium carbonate) is used.
- Water barriers, where the extinguishing agent is water.

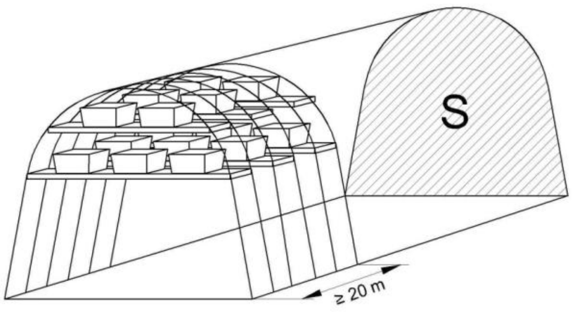

Fig. 4. Explosion barrier

Depending on the way of use barriers are divided on:

- ***Concentrated barriers*** (protecting determined working place where exists explosion ignition sources).
- ***Distributed barriers*** (protecting all workings, playing the role of inertization. Amount of extinguishing agent on the distributed barrier is established to 1 kilogram per cubic meter of the space).

About 70 % of coal mines protected by barriers in Poland and in the UK still use stone dust barriers, while water barriers are mainly used in Germany, Czech Republic and other European countries.

Deployment of the barriers in the workings had to take into account the possible ignition sources of explosion and properties of coal dust.

Water troughs must meet the ATEX Equipment Directive [6].

Water can be a very effective agent for flame suppression. It has a high heat capacity and an extremely high latent heat of vaporization, and absorbs infra-red radiation. In a flame it absorbs a large amount of heat by first being heated and then by turning to steam. But it is only effective if it is first broken into droplets. This is a difference from stonedust, which is already present as particles.

For the water in a trough to become droplets, it must be exposed to a sufficiently strong wind blast under favorable conditions. To achieve this, the face of the trough and the space above the trough must not be shielded from an oncoming explosion. This presents a problem of adequately supporting the frame without compromising the operation of the trough.

The main advantage of water barriers is the reliable protection of workings behind the barrier; there are many examples of very effective barrier actions.

The disadvantages of water barriers are:

- large dimensions, up to 50 m long;
- diminishing of the working cross section;
- need changing barrier position with movement of coal faces.

The problem of 'weak' explosions

Many of the precautions listed above will help to reduce the intensity of an explosion. However it is possible for a 'weak' explosion to propagate.

A 'weak' explosion in this context is not weak in terms of the damage it may cause. It refers to explosions at the low end of the speed range, with flame speeds from 30 m/s to about 100 km/h.

A weak explosion may propagate where reasonable (but inadequate) standards of stonedusting have been maintained. It could also occur where a fine layer of float coal dust overlies stonedust.

The explosion may not gain in intensity in this region, but it may continue to travel. If it manages to bypass other forms of protection (such as barriers) and reach the less protected roadways further from the face, it may then develop into a strong explosion and travel for great distances.

It is therefore essential that a backup protection, such as a barrier, is capable of stopping weak explosions.

III- AUTOMATIC EXTINGUISHER SYSTEMS

Standard EN 14591-4 [7] defines the characteristics that must fulfill the systems installed on roadheader designed to detect automatically the initial phase of an explosion of firedamp produced by the picks or cutting tools of the roadheader and to extinguish next to face roadway, so that the personnel working next to the roadheader remains protected.

The automatic extinction systems consist of a detector or transducer which reacts to selected explosion-specific phenomenon, for example, ignition, containers with an extinguishing agent in the form of powder or liquid and a system of control for monitoring with an operational element which, in response to an impulse received from the detector, puts the system into action and disperses extinguishing agent.

The main functionality requirements of the system are:

- High reliability design of operation (fail-proof design).
- High level of protection against incorrect shot, that involves a selective actuation and a minimal sensibility to external interferences.
- Protection Devices against not authorized interventions.
- Roadheaders operation is only possible with activated system.
- System of error detection.

The sensors must be sensitive to a physical variable that provides the maximum answer speed. Its detection status must be exact to the event explosion (not fires) and its reliability has not to turn affected by the presence of dust, water or the materials used in its construction.

Also they must fulfill the Standards according to the functional safety (EN 61508-1) [8] and electromagnetic compatibility (EN 61000-6-3) [9].
The deposits or containers where water is stored must be designed so that the discharge speed fits to the geometric conditions of the gallery, in particular the distance to the face, the radial dimensions of the gallery section and the direction of discharge with regard to the axis of the cutting arm.
There are used systems of extinction of high speed of discharge (named in the literature as HRD, high rate discharge) that are provided with a quick opening valve, in addition to the proper container, a flameproof enclosure and in its interior the proper fire extinguisher agent and the propellant consisting normally of pressurized gas.

The interval of time needed between the detection of the incipient explosion and the valve opening is only 3 ms and between the valve opening and the effective discharge of the extinguisher agent is comprised between 80 ms and 600 ms.
Other requisites that must fulfill these systems are:

- To support the mechanical loads of impact and vibration (support an acceleration forces equivalent to 5 g).
- To produce a minimal interference with the work.
- To leave space for the mechanical equipment: water diffusers, platforms
- Access adapted for maintenance and repair.
- Simple design that makes servicing easier and more cost effective maintenance and routine examination.

CONCLUSION

Dust explosion prevention and protection measures can be hierarchically organized from most to least effective in terms of measures related to: inherent safety (minimization, substitution, moderation and simplification), passive engineered safety, active engineered safety, and procedural safety.
Consideration of all levels in this hierarchy of controls is required for effective dust explosion risk reduction.

All processes should be carefully studied based on the best knowledge in this field in order to anticipate potential hazardous events and their probability.

Protection means against explosions in underground mines should be transformed and continuously improved, with the development of methods for estimating risk, improve safety management systems, emergency systems and emergency response to the potentially affected areas,
When assessing the risk of explosion and applying the protection means against dust explosion it is necessary to break away from the "mentality of the gas," and not to seek an analogy with explosive gases.

REFERENCES

[1] A. Szulik, K. Lebecki, and K. Cybulski Chapter 18. Risk of Coal Dust Explosion and its Elimination. Proceedings of the Fifth International Mining Forum 2004, Cracow - Szczyrk - Wieliczka, Poland, 24-29 February 2004.

[2] Amyotte P. R., Eckhoff R. K., Dust explosion causation, prevention and mitigation: An overview, Journal of Chemical Health & Safety, January/February (2010)

[3] Guideline for coal dust explosion prevention and suppression, Produced by Mine Safety Operations Division, New South Wales Department of Primary Industries (2001).

[4] UNE-EN 14591-1:2005 Explosion prevention and protection in underground mines - Protective systems - Part 1: 2-bar explosion proof ventilation structure defines the characteristics of the ventilation structures

[5] EN 14591-2 Explosion prevention and protection in underground mines - Protective systems - Part 2: Passive water trough barriers

[6] Directive 94/9/EC on equipment and protective systems intended for use in potentially explosive atmospheres (ATEX).

[7] EN 14591-4 Explosion prevention and protection in underground mines - Protective systems - Part 4: Automatic extinguishing systems for road headers

[8] EN 61508-1 Functional safety of electrical/electronic/programmable electronic safety-related systems -- Part 1: General requirements

[9] EN 61000-6-3 Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments