Experimental study for the application of water barriers to Spanish small cross section galleries

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Abstract
The objective of this work is the implementation of passive water trough barriers to put in practice EN-14591-2:2007 standard, as well as an update of the continuing study of passive water barriers. The viability of water barriers in typical Spanish small cross section galleries was analyzed and full scale testing at “Barbara” experimental mine in Poland was carried out. Suggestions for proper implementation of standards in Spain are presented.

Keywords: Full scale tests, Passive water barriers, Small section galleries, gas and coal dust explosion.

Estudio experimental para la aplicación de barreras de agua a las galerías españolas de pequeña sección transversal

Resumen
El objetivo de este trabajo es la implementación de barreras pasivas de agua para la puesta en práctica de la norma EN-14591-2: 2007, así como una actualización del estudio continuo de las barreras de agua pasivas. Se analizó la viabilidad de las barreras de agua en las galerías típicas españoles de pequeña sección transversal y se realizaron pruebas a gran escala en la mina experimental "Bárbara" en Polonia. Se presentan sugerencias para la correcta aplicación de las normas en España.

Palabras clave: ensayos a escala real, barreras pasivas de agua, galerías de sección reducida, explosiones de gas y polvo de carbón.

1. Risk of explosions in underground coal mines

The presence of flammable gas and coal dust in the mine atmosphere is one of the biggest safety problems in the underground mining of coal. Although there are significant technological advances, they have not succeeded in eliminating the problem as the increased production and mechanization and electrification of the work contribute to this risk to remain. Today still very serious coal mine accidents occur, as the mine gas explosion at the Sago Mine in West Virginia, USA that left 12 dead on January 2, 2006, the Ulyanovskaya longwall coal mine explosion in the Kemerovo Oblast, Russia, killing 108 people on March 19, 2007, the La Preciosa coal mine explosion in Norte de Santander department, Colombia, leaving 21 miners dead on January 27, 2011, San Joaquin coal mine in Antioquia department, Colombia explosion of coal dust took place on June 16, 2010 killed 71 miners death or the likely explosion of coal dust that caused 169 miners killed on 27 December 2005 at Donfeng mine in Heilongjiang province, China, a country which unfortunately declares numerous and continuous explosions in coal mines, throwing thousands of deaths every year.

In the last 25 years the Spanish mining industry has suffered only two underground explosions in the same exploitation system. The first one was in 1995 with 14 fatalities and the second, was in 1998 with two died miners. In both collieries, the reason of primary explosion was the firedamp accumulations in the roadway, which exploited and resulted in the propagation of coal dust explosion; mainly, the final reports concluded that the explosive atmosphere was built up in both cases by one coal burst.

The firedamp adsorbed in coal mines can continuously release by decreasing pressure, increasing temperature, fragmentation of coal due to pressures from the field and any changes in physical conditions thereof [1]. Dynamic gas

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phenomena may also occur in some deep mines. But the greatest risk occurs as a result of desorption that takes place at the coal face, which is correlated with the mining speed.

Due to its low specific gravity, methane tends to migrate toward the roof of the galleries, and its diffusion into the mainstream is a slow process. Methane tends to accumulate in both chambers in the roof in places and high points, and it is difficult to detect in such cases. The accumulation of methane in these cavities can significantly be often higher than usual concentrations in the workings.

In addition to firedamp, it is essential to consider the risk due to coal dust [2]. At any mine dust is generated during normal operations associated with the mining and coal dust is an element that can generate flammable explosive atmospheres. Unlike firedamp whose characteristics are very stable, coal dust varies greatly in its characteristics of flammability and explosiveness, which was found to be very different in different coals. There is a correlation between the explosion of different types of coal and its composition (proximate and ultimate analysis) [3]. In general, the higher the volatile matter content of coal, the greater its flammability.

To assess the risk of explosion due to coal dust, in addition to coal properties, it is necessary to consider the mining method and seam characteristics that affect dust production, accumulation and dispersion ability [4]. It is possible to apply traditional methods of risk assessment for specific mining explosions [5]. It should be noted that the presence of mine gas produces an increase in coal explosion due to gas adsorbed [6] or the presence in air of reduced concentrations of methane [7].

2. Passive explosion water barriers

Explosion barriers were known for long time and included among preventive and protective measures specific to mining, as the recommendations of the Permanent Safety and Health Commission for Coal Mines and other Extraction Industries [8], the traditional methods employed in mines in Poland with high risk of explosion [9] or the earlier forms of barriers against mine explosion [10].

Explosion barriers can be grouped into passive barriers and active barriers [11]. Passive barriers can be divided in stone-dust barriers and water barriers depending on the type of inert material used (incombustible stone dust or water). Water barriers are easier to maintain, less costly and as effective as stone dust barriers.

Passive barriers base their own performance in the kinetic energy of the pressure wave moving ahead of the flame front in an explosion. When the flame of the explosion reaches the water barrier, it has already been activated by the energy associated with the pressure wave, resulting in the dispersion of the inert matter in the path of the flame. To be effective, water or stone dust should be completely dispersed on the arrival of the flame front.

Water troughs barriers are self-protection systems designed to reduce the impact of the explosion, according to the directive 94/9/EC. They are designed and installed to prevent the spread of explosions and prevent incipient explosions escalating into stronger explosions or even the most devastating detonations. Passive water barriers simply consist of water filled containers, such as troughs, tubs and bags [12]. When an explosion occurs, the pressure wave turns over, decays or even destroys the water containers, pouring its contents, so water is dispersed by the turbulence of the air and creates a barrier formed by the dispersion of water droplets along the path of the flame. They are only effective under a design and layout precisely defined. When the barrier is properly positioned, the flame is extinguished. If the barrier is too far or too close to the source of the explosion, the flame cannot be effectively extinguished. Its effectiveness is based on the dispersion in the entire cross section of the gallery of water in the troughs when caught by the pressure wave that precedes the explosion, thus acting as a means for extinguishing the flames of the explosion that followed behind.

There are two types of explosion barriers: concentrated and distributed barriers. The concentrated barriers contain at least 200 litres of water per square foot gallery section and its length is at least 20 m and contains a minimum of 5 litres of water per cubic meter of gallery between the beginning and the end of the water barrier. Distributed barriers contain a minimum of 1 litre of water per cubic meter of gallery in the section between each set of troughs and the next group. The distance between adjacent groups of troughs should not exceed 30 m (50 m for a gallery section under 10 m^2).

The European Standardization Organization (CEN) has published the standard EN 14591-2 [13] with the requirements for the use of water barriers, their construction, and components. The most important elements of the barrier are the water troughs deployed in the workings. According to that standard "Water troughs barriers are designed and arranged in such a way that explosions are prevented from spreading through dangerous chain reactions and incipient explosions do not become detonations". Barriers are deployed in determined distance from the expected ignition point and that means they do not protect the section room between the ignition point and the barrier itself.

There are special types of concentrated and mobile water-trough explosion barriers [14] that could be moved along with the heading machines, so that when the front moves forward, the distance between the face and the barrier can be maintained within the application range, but the spatial conditions must be examined in depth to see whether the necessary explosion protection will be guaranteed.

If the suppressant is dispersed prematurely, its concentration is diluted before it reaches the flame. When the suppressor agent is dispersed too late it goes after the flame and has minimal effect on the extinction of the flame. To avoid these drawbacks, the active barriers incorporate trigger mechanisms, which consist of three main components: the sensor, the distributor and the suppressor. A sensor device detects the arrival of the blast by the increase of the static pressure, temperature or radiation and triggers a mechanism to disperse the suppressor agent. The discharge is produced by a compressed gas, a spring or explosive materials [15].

3. Implementation of water barriers in Spanish coal mines

Among underground coal mines in Spain, the Asturias region was considered as an adequate place to implement water troughs barriers in the workings.

Table 1.
Explosion parameters of some coal dust in northern Spain

COAL	TMIc (ºC)	TMIn (ºC)	LIE (g/m^3)	EMI (mJ)	Pmax (bar)	Kmax (bar.m/s)
Brown lignite	240	400	90	180	8,4	130
Black lignite	250	490	120	70	8,7	147
Bituminous coal	>400	630	30	>1000	6,2	90
Anthracite	>400	740	NI	NI	6,7	23

Source: Adapted from García Torrent, J, et al. 2001

Experience in underground coal mining in Spain has been limited to experimental sporadic uses of passive water barriers in some individual galleries [16]. Actually in the underground mines the passive barriers are not in use as protection systems for limiting the spread of the coal dust explosions, because:

- Particular coal properties – moderate volatile content combined frequently with high ash content;
- Not very large methane emission from the seams.

Explosion parameters shown in Table 1 of some Spanish coal dust were determined by Laboratorio Oficial Madariaga (LOM):

Those mines are characterized by:

- Relatively small workings cross sections, rarely greater than $12m^2$;
- Coal extraction mainly by the "sublevel" techniques with use of explosives.

These factors diminish the risk of coal dust explosion, but the risk reduction is not completely obtained [17].

The most dangerous places are coal faces where shot firing is performed.

3.1. First steps to study the viability of water barriers

According to preliminary study of viability it is recommended to follow several steps:

- Select one or two places where the risk of coal dust explosion is the highest according to the view of mine management as suitable places for installation of water trough barriers.
- Supply all material as water troughs, supporting elements, such as wooden shelves or metallic frames and others
- Install the barrier in the cross section according to one possible arrangement.
- Observe reaction of the mine crew and explain the idea of explosion barriers.
- Assess the explosion risk in mine workings taking into account the coal properties, amount of settled coal dust, its humidity and incombustible content to establish the places where barriers should be installed.
- Develop coal company safety regulations for explosion prevention and protection including settled dust inertizing and then study their extension to national guidelines.
- Train all mining engineers and mine staff in explosion protection.

4. Demonstration of water barrier effectiveness

Three water barriers full-scale tests at Barbara Experimental Mine were performed in order to:

- Demonstration of water barrier effectiveness in a strong explosion case, with water troughs of 40 liters, 50 m^3 methane, 100 $kg/m^2$of cross section
- Demonstration of water barrier effectiveness in weak explosion case with water bags, 25 m^3 methane, 100 kg/m2 of cross section.
- Demonstration of water barrier effectiveness in strong explosion case with mixed water troughs of 40 liters and 80 liters, 50 m^3 of methane, 100 l/m^2 of cross section.

4.1. Full-scale test specifications

Tests were carried out in the 400 m long underground gallery (Fig. 1) having 7.5 m^2 of cross section, which reflects the conditions present in most common galleries in the Spanish mining industry. On the cross section 2-2 the side shelves sections and crossbars are shown. Both elements serve to deploy the dust along the gallery. The enforced concrete gallery is built to withstand the explosions up to 45 bar. At the wall the sensors of flame and pressure are mounted. Flame sensors are positioned every 20 m, pressure sensors are placed every 20 m at the first 100 m, and every 40 m after that.

As an ignition source a methane chamber with two possible volumes of 25 m^3 and 50 m^3 was applied, with 4.5 kg of coal dust deployed in front of the paper baffle closing the methane chamber.

The objective of the test is to show that the explosion propagation is stopped when using the installation requirements defined in the standard EN 14591-2.

The chamber is filled with methane/air mixture in concentration about 9.5% (stoichiometric mixture) and ignited with a detonator. Primary explosion of methane gives sufficient blast and temperature to lift and ignite coal dust in front of the chamber and consequently start the coal dust explosion at the gallery.

The tested water trough barrier was arranged at a distance of 100 m from the closed end of the gallery and extended up to 121 m. This barrier contains 100 l of water per square meter of roadway cross section. Such amount is half of that required by standard EN 14591-2:2007 and is used in most national regulations to demonstrate the barriers effectiveness. In practice double amount is used to enhance the barrier reliability. Tested barrier was placed inside the dusty zone to be sure that explosion propagation is interrupted by the action of barrier and not by lack of dust in the gallery.

All tests were performed using the same type of coal dust (bituminous coal similar to Asturias coal but with less ash content). The total amount of this dust deployed on side shelves and roof bars was 340 kg with 38.5% of volatile content.

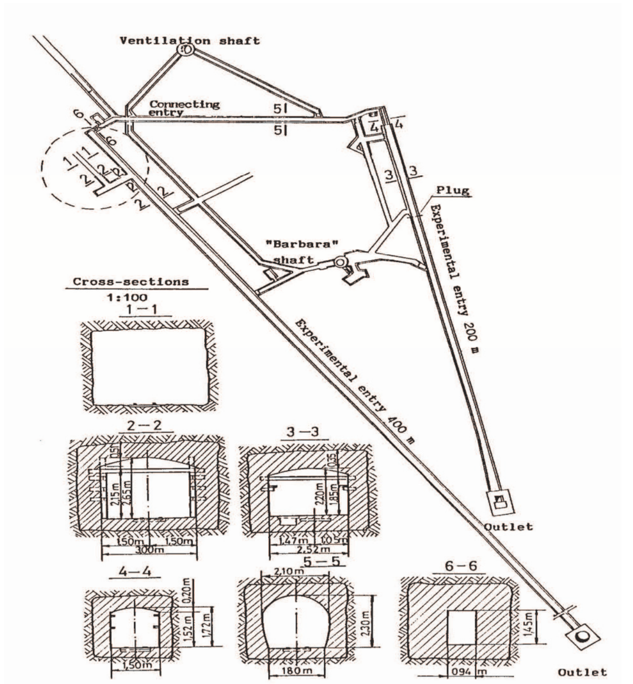

Figure 1. Underground Experimental galleries in the Experimental Mine "Barbara".
Source: Cybulski, W, 1975

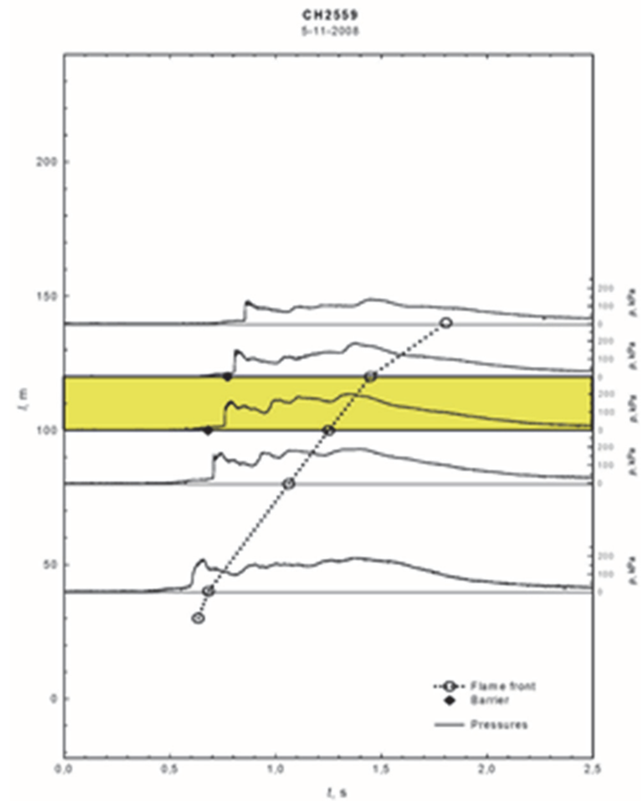

Figure 2. The water barriers efficiency in case of strong explosion with 40 l water troughs
Source: Laboratorio Oficial J.M. Madariaga – Central Mining Institute, project code: 080601001-13

4.2. Test 1: demonstration of water barrier effectiveness in strong explosion case, with water troughs

Test conditions for strong explosion, with water troughs of 40 l were:

4.2.1. Ignition source

In 6-6 gallery cross-section the gas chamber was filled with a volume of 50 m^3 having a 9.5% methane/air stoichiometric mixture closed with a paper baffle. This mixture was ignited with 500 g of black powder in the mortar and was ignited by a detonator. In front of the chamber, along a 2.5 m length gallery, 4.5 kg of coal dust mass were spread with a nominal concentration of 0.250 kg/m^3. Coal dust was deployed on the horizontal shelves. When the methane explosion was started the blast wave lifted the coal dust and dispersed it in the air, and the proper dust explosion was initiated in the gallery. This dust contained 38% material passing 0.075mm sieve (200mesh). The volatile content of coal dust sample was 38.5%.

4.2.2. Dust zone

156.6 m of 6-6 gallery contained coal dust on side shelves and roof bars. The total amount of deployed coal dust was 340 kg and the nominal dust concentration in the dust zone was 0.300 kg/m^3.

4.2.3. Water trough barrier

Water troughs were supplied by the Polish manufacturer Radom and they were certified according to EN-14591-2:2007. The water barrier was composed by a total of 7 rows with 3 troughs of 40 liters volume in each row. The horizontal distance between two rows was 3 m and the total length was 21 m. The water troughs were set from 100 m up to 121 m of the gallery.

The total water amount was 840 liters, 120 liters in each row and water concentration in barrier location was 5.3 kg/m^3 or 112 l/m^2.

Fig. 2 shows the test record. The Y axis represents distance travelled by the flame front and the X axis represents the needed time; pressure waves are plotted at different distances and the flame front path is drawn by the dotted line. The yellow zone corresponds to the barrier disposition. This figure indicated that the dust explosion was stopped inside the zone of the gallery where coal dust was still present, a little beyond the position of the barrier.

A view of the gallery after explosion showed that all containers were crushed into small pieces and were dispersed by the explosion blast along a distance up to 240 m of the gallery, then 120 m from the barrier.

4.3. Test 2: demonstration of water barrier effectiveness in weak explosion case with water bags

Test conditions for weak explosion, with water bags of 40 l were:

4.3.1. Ignition source

In 3-3 gallery cross-section the gas chamber was filled with a volume of 25 m^3 having a 9.5% methane/air stoichiometric mixture closed with a paper baffle. This mixture was ignited with 500 g of black powder in the mortar and was ignited by a detonator. In front of the chamber, along a 2.5 m length gallery, 4.5 kg of coal dust mass were spread with a nominal concentration of 0.250 kg/m^3. Coal dust was deployed on the horizontal shelves.

4.3.2. Dust zone

153.3 m of 3-3 gallery contained coal dust on side shelves and roof bars. The total amount of deployed coal dust was 340 kg and the nominal dust concentration in the dust zone was 0.300 kg/m^3.

4.3.3. Water bags barrier

Water bags were supplied by Minova. The water barrier was composed by a total of 7 rows with 3 bags of 40 liters volume in each row. The horizontal distance between two rows was 3 m and the total length was 21 m. The water troughs were set from 100 m up to 121 m of the gallery.

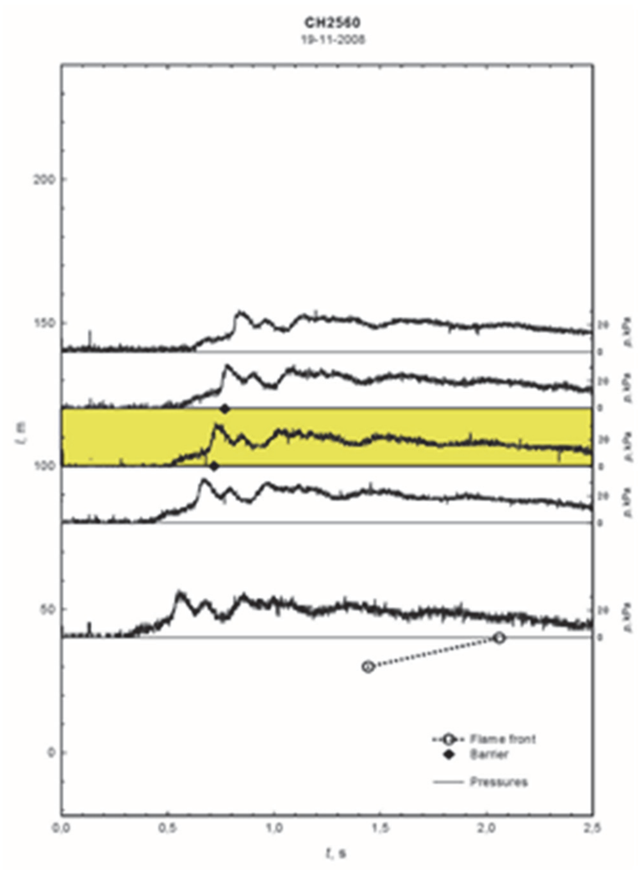

Figure 3. The water barriers efficiency in case of weak explosion with water bags.
Source: Laboratorio Oficial J.M. Madariaga – Central Mining Institute, project code: 080601001-13

The total water amount was 840 liters, 120 liters in each row and water concentration in barrier location was 5.3 kg/m^3 or 112 l/m^2.

The test record (shown in Fig. 3) indicated that the dust explosion was not stopped. A view of the gallery after explosion showed that no changes observed, water bags are untouched, because explosion was too weak to disperse the water of the bags.

4.4. Test 3: demonstration of water barrier effectiveness in strong explosion case with mixed water troughs

Test conditions for strong explosion, with water troughs of 40 l were:

4.4.1. Ignition source

In 6-6 gallery cross-section the gas chamber was filled with a volume of 50 m^3 having a 9.5% methane/air stoichiometric mixture closed with a paper baffle. This mixture was ignited with 500 g of black powder in the mortar and was ignited by a detonator. In front of the chamber, along a 2.5 m length gallery, 4.5 kg of coal dust mass were spread with a nominal concentration of 0.250 kg/m^3. Coal dust was deployed on the horizontal shelves.

4.4.2. Dust zone

156.6 m of 6-6 gallery contained coal dust on side shelves and roof bars. The total amount of deployed coal dust was 340 kg and the nominal dust concentration in the dust zone was 0.300 kg/m^3.

4.4.3. Water trough barrier

Water troughs were supplied by the Polish manufacturer Rybnik and they were certified according to EN-14591-2:2007. The water barrier was composed by a total of 7 rows (6 rows with 3 troughs of 40 l volume in each row and one row with two troughs of 80 l volume). The horizontal distance between two rows was 3 m and the total length was 21 m. The water troughs were set from 100 m up to 121 m of the gallery.

The total water amount was 1125 liters, 120 liters in each row and water concentration in barrier location was 5.3 kg/m^3 or 150 l/m^2.

The test record (shown in Fig. 4) indicated that the dust explosion was stopped inside the barrier zone.

A view of the gallery after explosion showed that all containers were crushed into small pieces and were dispersed by the explosion blast along a distance up to 280 m of the gallery, then 160 m from the barrier.

5. Discussion

Tests 1 and 3 probed and adequate efficiency of water barriers to stop strong explosions, even using half the amount of water needed. The explosion records did not leave any doubt about the actuation of the barrier and the inspection after test allowed to verify the correct operation of the water troughs. Both types of water troughs proved their validity as it should be since both were certified.

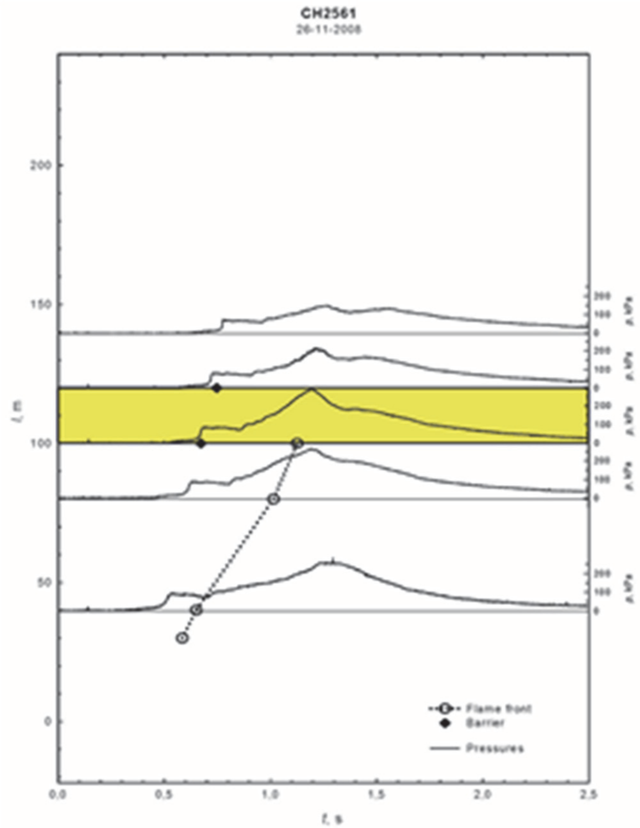

Figure 4. The water barriers efficiency in case of strong explosion with mixed 40 l+80 l water troughs.
Source: Laboratorio Oficial J.M. Madariaga – Central Mining Institute, project code: 080601001-13

Water barrier arrangement used in test 3, consisting of a mixed distribution of 40 liter and 80 liter trough can be considered as more adequate for the Spanish mines, because more flame traces have been registered by the sensors for the 40 l distribution water troughs than for the mixed distribution of 40 liter l + 80 liter troughs showing that the explosion was contained sooner with the mixed trough distribution

Regarding the weak explosion produced during test 2, some uncertainty was present because it was thought that several factors might interact to prevent the proper functioning of the water barriers. In fact, low explosibility coals or coals with a high degree of incombustible matter produce weak explosions, specially when the initiation is not too strong. As a result, the blast pressure of the explosion can be well below 1.5 kPa, the tanks cannot work properly, so that the dispersion of water is not effective enough to extinguish the flame front and the explosion continues beyond the barrier.

The reason for including a weak explosion in the test series is justified because the likelihood of a failure in the activation of the bags is around 30 % of the test performed. It has been shown during the test that the water bags are suitable for strong explosions but they are not for weak explosions with pressures around 30 kPa or less.

To check the different behaviors between water troughs and bags in case of weak explosions a similar test was carried out in a 400 m experimental gallery with mixed distribution of water bags and troughs. The interesting thing was that the water troughs placed at the distance of 180 m from the ignition source were blown off, whereas the water bags hanged at the distance 100 m from ignition source were not deteriorated and the explosion was not stopped.

As a result it was felt that the behavior of the water bags could be critical, resulting in a failure to arrest the explosion. Moreover these bags do not appear on the EN 14591-2 standard, so it was decided not to try them and reject their use in the Spanish mines, where coal characteristics often may produce weak explosions rather than strong explosions.

Based on the obtained results and the analysis of the Spanish roadways, the suggested set-up for distributed water barriers is:

- The trough groups shall cover the greatest width of the roadway cross-section (floor width or roadway diameter) at the point of installation
- The achieved coverage is 80% (90 liter-type A troughs), 67% (40 liter-type A troughs) and 78% (all type B troughs)
- The vertical distance between the bottom of any trough and the boundary of the roadway cross section shall not exceed 2.6 m in downward direction.
- The vertical distance is 2.2 m (90 liter-type A troughs), 2.0 m (40 liter-type A troughs) and 2.2 m (all type B troughs).
- The distance between rows is less than 2 m.

6. Conclusions

Spanish coals are not extensively explosive, being characterized by relatively low volatile content (frequently less than 15%) and high ash content (average about 30%) . These two factors diminish the explosion risk. Water barriers will be implemented after detailed risk assessment in the workings where there is an elevated explosion risk. This evaluation should include a thorough analysis of the flammability characteristics of coal dust and the feasibility of inerting coal dust should always be considered.

A general conclusion obtained from the underground tests is that passive water barriers are effective in the arrest of coal dust explosions in galleries of reduced section. The effectiveness greatly depends on the configuration of the barriers. The test at the mixed configuration (40 and 80 liter troughs) has yielded the best results.

For reduced section galleries with unobstructed sections the installation of passive water barriers according to the EN 14591-2 is possible. However, the execution of mining works in reduced section galleries together with the installation of different equipment significantly reduces the effective section and it is very difficult or even unfeasible to install passive water barriers as required by EN 14591-2.

For many existing forms of mining in Spain (longwall, and soutirage sublevels by room and pillar) the EN 14591-2 standard does not specify clearly which are the locations for installing passive water barriers. The standard can be difficult to be properly applied as it is necessary to draft a guide and perhaps some additional rules or regulations.

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