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PREVENTION AND PROTECTION AGAINST PROPAGATION OF EXPLOSIONSIN UNDERGROUND COAL MINES*

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Over the past century, the coal mining industry experienced a large number of explosions leading to a considerable loss of life. The objective of this study is preventing the propagation of methane and/or coal dust explosions through the use of passive water barriers and its implementation to the Spanish coal mining industry. Physical and chemical properties, flammability and explosibility parameters of typical Spanish coals are presented. In this paper, a flexible approach to meet the requirements of the EN-14591-2:2007 standard is presented for the very specific local conditions, characterized by small cross-sections galleries, vertical seem, use of explosives, etc.

Authors have proven the viability of standard requirements to the typical roadway from Spanish underground mines, considering realistic roadway lengths as well as available cross-sections taking into account ubiquitous obstacles such as: locomotives, conveyor belt, ventilation ducts, etc.

***Key words*:** Passive water barriers, Spanish coal mines, methane explosion, coal dust explosion, dust inerting

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Introduction. An underground coal dust explosion involves several stages that can be summarized as follows [1]:

• formation of an explosive methane/air mixture;

• ignition of the mixture;

• development of the primary gas explosion;

• lifting of coal dust by pressure front of primary gas explosion and creation of the dust/air mixture;

• turbulent acceleration of the dust flame front, lifting more dust and creating an explosive zone in front of the flame;

• propagation of a dust explosion throughout the whole mine.

The first line of action to prevent explosions in mines is the implementation of preventive measures against both firedamp and coal dust [2].

Among preventive measures against firedamp, in simplified form, when emissions are low and gas is slowly released, the effect could be minimized with adequate ventilation. When gas is emitted as a continuous breath, airflow can be removed by sealing outlets through drainage techniques or just increasing the ventilation of the area to promote dilution. For higher emissions other preventive means should be considered, such as facilitating the partial release of gas with short drills for degassing and also by water injection.

Regarding coal dust, Spanish regulation provides that «measures must be taken to reduce flammable dust deposits, and proceed to safe disposal» [3, 4].

Preventive measures can be summarized in the following [5, 6, 7]:

• avoid accumulations of dust, especially if this is fine and dry. This requires to schedule a cleaning and maintenance program to prevent the formation of deposits. The points to be addressed with greater attention are those where dust tends to accumulate: near the start of the mine cut, at the bottom of inclined planes, beneath the conveyor belts at the transfer points, loading and unloading, dumping, storage, etc;

• water injection into the solid by short holes perpendicular to the front and by parallel long hole to the front to decrease dust production;

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• dust entrapment can be achieved through irrigation, which is cheap and simple, but may be ineffective, due to water evaporation. Another method to fix the dust is the use of hygroscopic salts. These, commonly $CaCl_2$ and $MgCl_2$, mixed with wetting agents, provide a binder solution that becomes a kind of crust of the deposited powder, thereby preventing its dispersion. There are three different ways of using the hygroscopic salts: as pastes, powders or flakes [8];

• the dusting of inert material on coal dust in certain proportions is suitable to prevent it from spreading an explosion along the galleries where it is deposited. The amount of inert powder required may vary between 55 % and 80 % by weight [9].

An explosion requires the simultaneous appearance of five factors, forming the so-called explosion pentagon: Combustible, oxidizer, mixing, ignition and confinement. [10].

The lack of one of the elements of the pentagon or braking connection between them excludes the appearance of the explosion. In the case of an 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 works;

• underground mine workings are confined spaces 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.

Explosion protection can be established in successive stages. The purpose of primary explosion protection is to substitute 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. [11, 12, 13]. 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 coal dust deposits 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: the avoidance or restriction of substances which are capable of forming an explosive atmosphere and also to the avoidance or restriction of release of the flammable substances and therefore formation of explosive mixtures.

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.

Action directed at tertiary explosion protection aims to override the harmful effects of explosions and thus to 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.

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The aim of protection measurements is to prevent that the explosion will become increasingly important when propagating once it has started. 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 the sooner the explosion stops, fewer consequences will result.

If prevention measurements, such as limitation of coal dust generation during workings or elimination of ignition sources or neutralization of the settled dust by adding of incombustible matter, fail the passive barriers are the only way to protection, preventing the explosion flame front to propagate throughout the whole mine.

Explosion prevention by means of inerting dust. Inerting is a method of preventing the spread of a primary explosion. The method consists of the addition of inert powder (called sterile or diluent powder) to coal dust so as to form a mixture whose explosion parameters are reduced.

The application of inert powder has two purposes: it prevents dust dispersion, and also prevents participation of coal dust in an underground explosion. This is possible because inert dust acts as a heat sink (adsorption energy), provides a shielded radiation of the flame front and impedes the kinetics of combustion. The inert dust dilutes the concentration of coal dust and prevents oxygen or other gases to take part in an explosion.

Spanish regulations do not establish any minimum value for the concentration of inert dust in the mixture. However, foreign regulations fix the necessary percentage of inert dust, according to the characteristics of the mine or coal.

The minimum recommended requirements for inerting have been calculated using the method developed by some of the own authors [14, 15]. This method allows to calculate theoretically the percentage of inert (including moisture and ash) in the absence of firedamp that would be required to add to each carbon.

The calculation is based on the correlation existing among chemical composition and explosibility of coals. Two canonical variables are experimentally obtained: firstly, a set of variables, that are determined in the laboratory to chemically characterize a type of coal and secondly, a set of variables that characterize the explosibility of the coal:

$$VC_{12} = f(C, H, S, M, Cs, V);$$

$$VC_{11} = f(T_{\min}, LIE, EMI, P_{\max}, K_{\max}).$$

The first set is a linear combination of the variables related to chemical analysis, where C is carbon content; H is hydrogen content; S is sulfur content; H is moisture; Cs is the ash content; V is the content of volatile

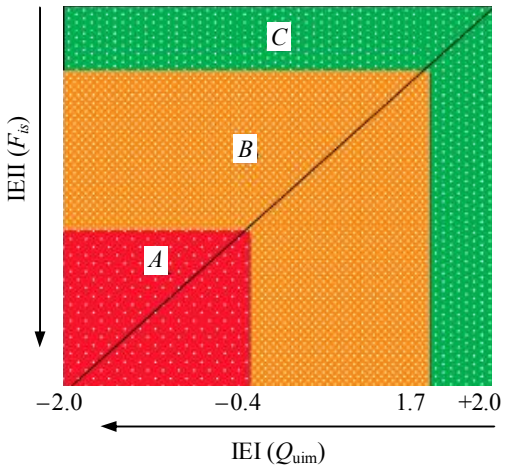
The canonical variable VC_{12} has all the characteristics of proximate and ultimate analysis of coal. Obviously, the volatile content carries more weight on VC_{12} than other coal characteristics, but its advantage lies precisely in considering the influence of all the features.

$$VC_{12} = -3.05 + 0.052C - 0.039H + 0{,}041S - 0{,}012W + 0.064A - 0.057V.$$

The second set of variables VC_{11} refers to linear combinations of the variables related to the parameters of explosion, where, $T_{\min}$ is the minimum ignition temperature; LIE is the lower explosive limit; EMI is the minimum ignition energy; $P_{\max}$ is the maximum pressure; $K_{\max}$ is the pressure rise constant.

The canonical variable VC11 takes into account the values of the parameters of ignition sensitivity and severity of explosion. According to the values that reach VC12 and VC11, usually very close quantitatively, coal dust is considered more or less dangerous. This method of canonical variables provided a graphical descriptive representation of the behavior of coals. A canonical diagram in which the values of the corresponding canonical variables representing each sample is readily obtained. As a result of a statistical study of values for coals of various ranks and origins established

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Canonical diagram for coals [14, 15]

that the values $VC_{12} = VC_{11} = -0.4$ and $VC_{12} = 1.7$ marked the boundary between three types of behaviors of coal dust (Figure).

Accordingly, three zones are distinguished in the diagram:

A = High Sensitivity and Severity,

B = Moderate Sensitivity and Severity,

C = Low Sensitivity and Severity.

It is also possible to calculate theoretically the percentage of incombustible material (water or stone dust) that would be required to add to each coal located in areas A or B to take it to the «safe area» C, that is, to inert it.

To find the percentage of inert to be added to a particular type of coal to inert it and place it in the «safe area» C the following equation is recommended: $Z = (VC_{12} \times \times 100\text{-}170)/(VC_{12}\text{-}3.35)$.

Where $Z = X + Y$, Z = % inert to add X = % sterile powder added Y = % water added.

Experience has shown that very good agreement between the calculated values and those determined experimentally in the laboratory and full-scale test galleries is obtained. [16]

Canonical variables usually range between –2.0 and +2.0.

For a more intuitive understanding of its meaning two explosion indices, called Chemical Index (IEI) and Physical Index (IEII) are often used. They are immediately obtained from the canonical variables:

$$\text{IEI (Chemistry)} = 2 - VC_{12},$$

$$\text{IEII (Phys)} = 2 - VC_{11}.$$

As an example of calculation of the canonical variable, Table gives the canonical variable values and percentages of inert that are required for different coals.

Chemical analysis for different coal samples leading to the required inert percentage

Coal	C	H	S	W	A	V	VC_{12}	$Z = X+Y$ (%)
Teruel	58.9	3.7	6.8	2.8	13.8	33	–0.88	61.0
Pittsburgh	77.1	5	1	1.75	6.5	35.9	+0.85	60.7
Asturias	70.1	4.7	1.7	0	9.7	37.6	–1.04	62.4

Source: Adapted from [17].

Explosion protection. European Standardization Commission (CEN) issued the standard EN 14591-2:2007 «Explosion prevention and protection in underground mines – Protective systems – part 2: Passive water trough barriers» [18] requiring the use of water barrier, their construction, components, deployment, ways of use, marking, etc. The most important elements of the barrier are the own water containers (called also water troughs) deployed in the workings. According to EN-14591-2 «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 expected ignition point what means do not protect the room between ignition and barrier itself. This standard works very well in the large workings cross section, as those present in Germany or in the majority of Polish coal mines. Standard is well known in Spanish coal industry but its implementation in the local conditions will require a flexible approach [19].

After an exhaustive study of the previously mentioned standard as well as other pertinent references, the Laboratorio Oficial J.M. Madariaga (LOM) and Laboratory of the Experimental Mine «Barbara» in Poland carried out a research study, considering the characteristics of the most usual Spanish collieries and work face conditions to be found in the underground installations of the main coal mining industry companies [20].

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Explosion barriers are divided into two groups depending on the extinguishing agent used: Stone dust barriers, where inert dust (mainly calcium carbonate) is used and Water barriers, where the extinguishing agent is water.

Depending on their mode of use, barriers are divided into:

• concentrated barriers (protecting determined working place where exists explosion ignition sources);

• distributed barriers (protecting all workings, playing the role of inertization. The 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.

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:

• big dimensions, up to 50 m long;

• diminishing of the working cross section;

• necessity of changing barrier position with movement of coal faces.

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

In Spanish underground coal mines this factor differs considerably from other European countries, and that means that water barriers installation should be performed in a slightly different way than described in standard EN 14591-2:2007.

To analyze the influence of the particular characteristics of Spanish coals, data from various samples were considered. Based on the existing correlation between coal composition and explosibility of dust, some composition parameters were studied. So, humidity content of coal samples ranged from 2 to 20 %, ash content from 5 to 50 % and volatile matter from 6 to 35 %. Generally, these results say that explosibility of coal dust in Spanish mines is moderate with relatively low volatile content and high ash content. Taking this into account, one can say that the need of water barriers in the spirit of EN 14591-2:2007 Standard in Spanish coal mines is limited. This spirit supposes covering the whole mine with concentrated and distributed barriers, which seems to not have a big sense in some Spanish coal mines, depending on the explosion parameters of the particular coal.

In order to achieve final object of this research project, the use of barriers is proposed in selected places, such as:

• faces where blasting is performed;

• places with frequent methane accumulations;

• other places where coal extraction is performed.

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 as follows:

• at least 35 % for roadway cross-sections of up to 10 m^2;

• at least 50 % for roadway cross-sections of up to 15 m^2;

• at least 60 % for roadway cross-sections of over 15 m^2.

Conclusions

Water barriers protect against flame propagation behind the barrier and do not protect the space between ignition source and barrier itself. Water barrier effectively suppress the flame propagation but not the pressure wave which runs along the working up to being suppressed by flow resistance. Water barriers or passive barriers generally are the last part of the protection system- or one of the last layers of protection. One important conclusion could draw – inerting of the settled dust is necessary.

The main conclusions obtained after the preliminary study are the following ones:

It is necessary to perform a formally documented hazard analysis before undertaking any measures of prevention or protection. This analysis should include all important parameters of the coal dust explosibility.

Tests should be carried out using the configurations for the explosion tests for troughs described in Standard EN 14591-2:2007, especially in relation with the explosion overpressure range to be used during the tests. The tests can be carried out using both concentrated and distributed barriers. Nevertheless, the type of barriers to be tested is not completely defined at the present time.

Firstly prevention shall be applied and then protective measures. Before studying the viability of passive barriers installation, the possibility of coal dust inertization must be studied.

In those cases when it is unfeasible to install the passive water barriers according to Standard EN 14591-2:2007 a guideline for coal dust explosion prevention and suppression must be elaborated.

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