Chapter 2

MINE EXPLOSIONS

Mine explosions are caused by ignition of firedamp (fire damp explosions) or coal dust (coal-dust explosions) or both (mixed explosions). They are sudden combustion processes of great intensity which are accompanied by release of large quantities of heat energy and in which the original gas or solid coal substance is converted into gaseous products.

2.2- Firedamp Explosions

Methane burns in air when ignited with a pale blue flame but when it is mixed with air it can explode on ignition.

The combustion and explosion take place according to the equation

$$CH_4 + 2(0_2 + 4N_2) = CO_2 + H_2O+8N_2$$

One volume of methane requires two volume of oxygen or ten volumes of atmospheric air for its just complete combustion. Theoretically, therefore, the optimum or stoichiometric mixture is formed at 9.5 .per cent methane. Methane, however forms flammable mixtures with air over a range of approximately 5 to 15 percent.

If the methane content of a methane-air mixture is greater than 9.5 per cent, the oxygen present will not be sufficient for its complete combustion and if H is less than 9.5 per cent, oxygen or atmospheric air will be in excess.

2.1.1 Limits of Flammability or Flammable Limits

Flammable limits of methane-air mixtures are the limits of concentration of methane in air between which flame can be propagated throughout the mixtures. The boundary-line mixtures with minimum and maximum concentration of methane in air, which, if ignited, will just propagate flame, are known as the "lower and upper flammable or explosive limits". The lower and upper flammable limits are approximately 5 (33 g/m^3) and 15 (100 g m^a) respectively.

A mixture containing less than 5 per cent methane, although not flammable under normal conditions, may explode when at a high temperature or when compressed adiabatically due to blasting or a coal-dust explosion. Also, a mixture containing more than 15 per cent methane in which electric sparks can be generated without any explosion taking place is dangerous in a mine as it may become flammable on dilution with air in mine workings.

The limits of flammability are not fundamental characteristics of the gas but depend on experimental conditions. They are influenced by the presence of other combustible and inert gases, temperature, pressure, intensity of turbulence, diameter of experimental tube, direction of flame propagation, oxygen concentration, intensity of igniting source, and presence of coal dust.

The lower flammable limit of methane decreases linearly from 5 per cent to zero as the air-borne coal dust concentration increases from zero to its lower limit of flammability (Fig. 41)

The presence of other combustible gases like ethane, carbon monoxide, hydrogen etc. which have like methane lower and upper flammable limits also reduces the lower limit which can be determined by using the Le Chatelier relation:

$$\frac{100}{L} = \frac{P_1}{L_1} + \frac{P_2}{L_2} + \frac{P_3}{L_3} + ...$$

Where P_1, P_2, P_3 are percentages of component gases in the mixture ($P_1+P_2+P_3+$ ...... =100%) and L_1, L_2, L_3 …. their percentage lower limits.

The presence of inert gases has a damping effect on the flammability of methane-air mixtures. Carbon dioxide is more effective than nitrogen

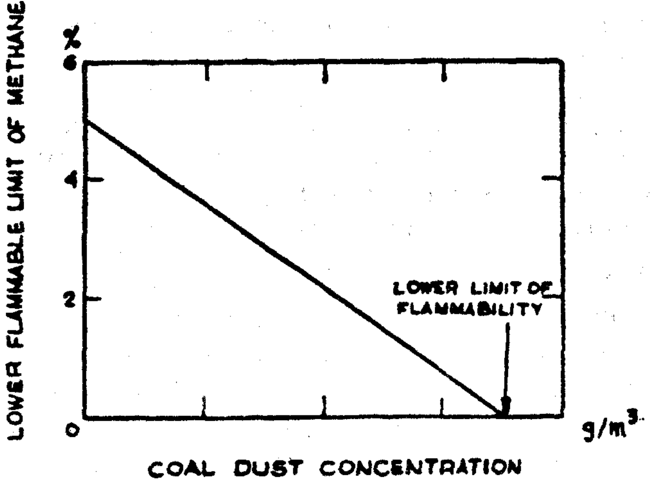


Fig. 41. Decrease of Lower Flammable Limit of Methane with Airborne Coal Dust Concentration

2.1.2 Ignition Point or Ignition Temperature

The ignition point of flammable firedamp-air mixture is given as 650° to 750° C. It is the minimum temperature to which a portion of it must be raised in order" to initiate or cause rapidly accelerating reaction in the whole of the accumulation with the accompaniment of flame and does not refer to the temperature of the igniting source which must obviously be at a higher figure. It is not a definite temperature but depends upon the nature of source of ignition whether flame, spark, etc., shape and size of space where ignition occurs, methane content, temperature of surroundings, pressure, oxygen concentration, presence of other gases, and turbulence. The ignition point of methane in oxygen is 556° C.

A characteristic property of firedamp is that when it comes into contact with an igniting source whose temperature is comparatively little above its ignition point, a certain time must elapse before it is ignited. This period is known as the "ignition lag" or induction time and it depends on temperature, pressure, gas concentration and presence of other combustible gases. Thus, Naylor and Wheeler [17] found that with a 6.5 per cent methane-air mixture and a source of heat at a temperature 790°C, the lag was 11 s, and when at 1175°C only 0.01s. The ignition lag is explained as due to the reaction of methane with oxygen only after it has absorbed a definite quantity of heat (22.1 kcal Mol) [18].

2.1.3 Explosion Characteristics

2.1.3.1 Flame Temperature

The flame temperature of flammable firedamp-air mixture is the temperature which occurs just at the moment of its explosion. It depends on the concentration of firedamp, uniformity of the mixture, turbulence, confinement, and heat losses. It is maximum at the stoichiometric concentration and is less at the lower and upper flammable limits. The temperature, however, does not remain constant but at once comes down to mine roadway temperature due to the explosion gases mixing with the rest of cooler air and also coming into contact with cooler roadway surfaces. The flame temperature of 10% methane-air mixture is given as 1870°C when the explosion gases are. free to expand (constant pressure).

2.1.3.2 Explosion Pressure

The explosion pressure depends on the flame temperature and confinement. The maximum explosion pressure of methane-air mixture (760 mm Hg, 20°C) when ignited in a closed vessel is given as 7.7 atg [19]. In mine workings, however, the explosion pressure may exceed this value. The shock wave (pressure wave) travelling ahead of the explosion flame will compress any firedamp accumulation encountered on its way to a pressure greater than 1 atg. Upon ignition of such accumulation, the maximum explosion pressure of the resulting explosion will be much greater than 7 atg. This explains the observation generally made that servere damage from a firedamp explosion does not occur at the seat of the explosion but away from it.

Experiments on gas explosion phenomena in the U.S. Bureau of Mines experimental coal mine (20] using natural gas (83% CH_4, 16% C_SH_8, and 1% N.) showed that highest explosion pressure occure in the gas zone and that the pressure decays exponentially with distance outbye the gas zone.

2.1.3.3 Flame Length

Experiments in the U.S. Bureau of Mines experimental coal mine [20] showed that the length of flame increases as the gas concentration in a gas zone increases from the lower limit of flammability to about 12% after which it decreases.

2.1.3.4 Velocity of Propagation of Flame or Flame Velocity

The velocity of propagation of a firedamp explosion flame is very small. It depends on the following factors.

1) Methane Content of Mine Air

The velocity of flame propagation increases with increasing firedamp content from the lower flammable limit upwards. After reaching the maximum value at the optimum concentration, the velocity decreases.

2) Condition of the Gas Mixture whether at Rest or in Motion

It has been found from experiments conducted in stationary mixtures m tubes that maximum velocity of propagation is not greater than 0.6 m/s [18). On the other hand, when the gas mixture is in motion, the velocity quickly increases to a few hundreds of metres per second.

3) Point of Ignition

The location of the point of ignition within the body of gas mixture markedly affects the velocity of propagation. If ignition takes place at the closed end of a roadway filled with gas mixture, the speed of propagation and severity of explosion are greater than when ignition takes place at the outbye end of the roadway. When ignited at the outbye end, rapid burning rather than explosion develops. It is for this reason that the "fire boss" m the early days of coal mining could purposely ignite gas as he entered a heading without initiating a dust explosion.

4) Length of Gas Zone

Experiments in gas zones in the U.S. Bureau of Mines experimental coal mine {20] showed that the velocity of flame propagation of a gas explosion increases from zero at the point of ignition to a maximum at a distance of about twice that of the original length of the gas body.

5) Presence of Objects or Obstacles on the Way or Change in Area of Cross-section of Roadway

If a roadway in which an explosion has occurred has objects or obstacles which decrease its area of cross-section, the velocity of propagation of the explosion rises to a few hundreds of metres per second.

2.1.3.5- Direct Blast and Backlash

Firedamp explosions are characterized by two distinct operations, the direct blast and the indirect blast or backlash. In the direct blast, a pressure wave of great force and speed travels ahead of the explosion flame. The backlash is caused by the vacuum arising out of cooling of explosion gases and condensation of water vapour and is of less intensity than the direct blast but traverses the same path backwards. When the concentration of methane is greater than 9.5, two types of explosion names appear, the primary and secondary flames. The primary flame propagates at a greater velocity and consumes the entire available oxygen. The secondary flame is produced by the later burning of the unbrunt gas with the help of oxygen supplied by the backlash. It propagates slowly in the direction opposite to that of the primary flame.

2.1.3.6 Explosion Gases

The chemical composition of the products of a firedamp explosion depends greatly upon whether it is a pure firedamp explosion or a mixed explosion of firedamp and coal dust. With a pure gas explosion, carbon dioxide is always formed and CO is frequently found. Certain amount of oxygen is also found in the explosion gases due to fresh air supplied by the backlash.

2.1.4 Causes of Firedamp Explosions

The various causes of firedamp explosions in mines may be grouped under the following headings :

Foolishness of miners
Use of damaged flame safety lamps and their improper handling
Blasting
Mine fires
Friction
Electric sparks
Other special causes

2.1.4.1 Foolishness of Miners

Smoking, making fire, or opening of safety lamps on the part of miners had in the past resulted in ignition of firedamp. Explosions from such causes reflect discredit on all concerned.

2.1.4.2 Use of Damaged Safety Lamps and Their Improper Handling

A safety lamp is safe only when its various parts are clean, in good condtiion, all parts are properly assembled, and is properly handled.

2.1.4.3 Blasting

Blasting in coal and road head rippings represented a dangerous source of ignition of firedamp in the past. With development of new and safer explosives and improved short-firing techniques during the past decade, the number of explosions due to this cause *hid* decreased considerably.

2.1.4.4 Mine Fires

Mine fires may easily bring about ignition of flammable firedamp mixtures in contact with them. When fighting a fire in a gassy mine, care should be taken to prevent firedamp content of mine air from rising to flammable proportions.

2.1.4.5 Friction

Frictional heating and frictional sparks can, under certain circumstances, ignite flammable flreadmp-air mixtures. Frictional ignition in mines can be broadly divided into (a) friction between' metal and metal, (b) friction between metal (especially steel) and rock, and. (c) friction between rock and rock.

The degree of ignition hazard from metal-to-metal contact is determined by the properties of the more readily oxidizable metal. Extensive , research carried out in Germany and the U.K. on the possible ignition of flammable firedamp mixture by incendive metal sparks have clearly shown that the ignition hazard from incendive particles of iron is extremely less and that danger may be feared only from aluminium and its alloys [21].

Friction between metal and rock poses the greatest ignition hazard in mines. Several firedamp explosions in mines in recent years have been attributed to frictional sparking during cutting and drilling operations in seams containing hard siliceous band or inclusions of iron pyrite nodules. Experiments showed that the nature of rock is far more important than the type of picks or bits used.

Some early mine explosions in the U.K. and Canada were attributed to friction between rocks caused by fall or-caving of sandstone roof rock. Experiments conducted in the U.K. showed that the ignition of firedamp by the impact of rocks may take place by its direct contact with the hot patches on the contacting rock surfaces and that siliceous or quartz-bearing sandstones can produce ignitions.

Despite extensive research, the exact mechanism of the ignition process is not well understood. The frictional ignition hazard depends on the nature of the contacting materials, the composition of the flammable gas mixture, the rate of energy release, and the type of frictional contact of the materials.

2.1.4.6 Electric Sparks

The electrification of coal mines has introduced into the mines an ever present source of ignition by electric sparks of not only combustible materials but also of flammable firedamp-air mixtures. Although electric sparks have usually a much higher temperature than ordinary flames, it may happen that a spark will fail to ignite a flammable gas mixture. This is due to the fact that a spark may have a very short life und its electrical energy may not be sufficient to cause ignition of the mixture in that time. The minimum energy of a spark causing an ignition of a flammable firedamp mixture varies with methane concentration, humidity, oxygen content of atmosphere, temperature, pressure, and turbulence.

The variation of minimum ignition energy with different methane-air mixtures is shown [22] in Fig. 42 from which it is seen that the most flammable mixture for ignition by an electric spark occurs at 8.3 per cent methane irrespective of the type of spark (low-voltage inductive or high-voltage capacitive) and that the minimum igniting energy is as low as 0.28 ml (mWs).

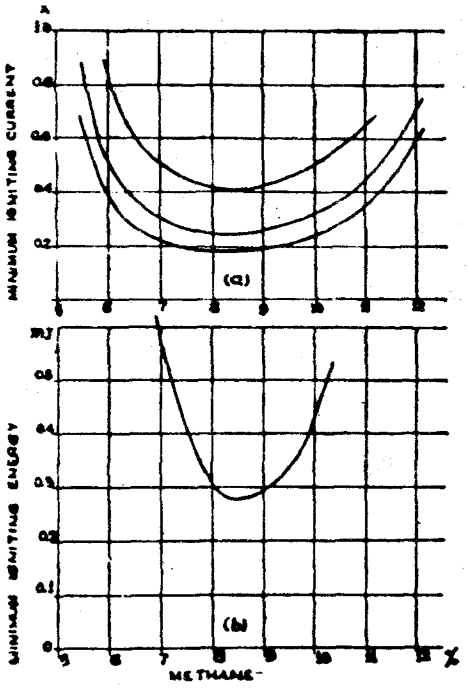


Fig. 42. Effect of Methane Concentration on the Ignition of Methane-Air Mixtures by Electric Sparks.
(a) ignition by low-voltage inductive spark.
(b) ignition by high-voltage capacitive spark.

2.1.4.7 Other Special Causes

Some of the mine explosions -in recent years have been ascribed to ignition of firedamp or dust-air mixtures by sparks of static or frictional electricity having adequate energy which will be some fraction of the total stored energy.

Ordinary belts passing over pulleys can accumulate static charges sufficient to produce sparks capable of igniting flammable firedamp or dust-air mixtures.

Dust-laden mine air passing through ducting can electrify the ducting by friction.

Warm dry atmospheres are favourable to the development of static charges by friction.

2.1.5 Prevention of Firedamp Explosions

No practical measures exist for arresting firedamp explosions in coal mines. Only protective measures against this hazard can be adopted.

The various measures against firedamp-explosion hazard in mines can be divided into the following three groups.

2.1.5.1 Measures against Accumulation of Dangerous Firedamp Mixtures in Mine Workings from the beginning.

The most effective method of preventing firedamp explosion in mines is to provide adequate ventilation which will dilute the firedamp, besides other harmful gases, to well below limits that may be prescribed for different mine workings and carry it away to the surface. Frequent sampling of mine air for methane at several points in the mine is, therefore, an important measure for prevention of firedamp explosions.

The following important points should be borne in mind:

(i) The mine should be mechanically ventilated. A reserve or standby main fan having an independent drive and power circuit should be provided especially in mines having methane emission greater than 5 m^3 per tonne of daily output.

(ii) The mine equivalent orifice should be as large as possible ($>2\ m^3$); higher ventilation pressures exceeding 200 mm WG should be avoided as far as practicable.

(iii) The entire mine should be ventilated by the exhaust ventilation method.

(iv) The ventilation of mine workings should not be done by diffusion alone.

(v) The ventilation of development headings should be done by utilizing the mine ventilating pressure as far as practicable. If auxiliary fans are required to be used, they should be installed and located in such a manner that recirculation of air is eliminated.

(vi) Ventilation doors should be correctly located and kept closed except when men, equipment, and trains are passing through them.

(vii) The mine ventilation system should be planned so that simple effective and reliable ventilation of all workings is assured.

(viii) The method of working or extraction should be selected so that it guarantees an easy and safe ventilation of the faces with adequate velocities in the face and at the waste edge. The number of working places served with auxiliary ventilation should be restricted to a minimum.

(ix) Air-leakage should a minimum.

(x) A particularly high standard of unit ventilation should be maintained in districts liable to outbursts.

(xi) Air currents and methane emission should be controlled by systemic measurement, of air quantities and their methane concentration. Special examinations for firedamp layering should be made during periods of falling barometric pressure in roadways adjacent to old workings and within the areas of moving ground behind faces.

2.1.5.2 Measures against Ignition of Firedamp Mixtures

The various preventive measures against ignition of flammable firedamp mixtures in mines are:—

(i) All persons should be prohibited from carrying smoking articles, matches or other spark or flame-making devices,

(ii) All coal mines should be treated as safety-lamp mines as a number of explosions in the past had occurred in the so-called naked-light mines. In short-life naked-lamp mines where naked lights are to be retained, special attention should be paid to ventilation, gas testing, and to precautions against coal dust.

(iii) Only approved types of flame and electric safety lamps should be used. The safety lamps should be properly maintained and carefully used. The following precautions should be observed when using flame safety lamps:

(a) The lamp should be carried in vertical position.
(b) The glass should be protected from splashes of water.
(c) The lamp should not be set down on the floor but should be hung from a substantial support.
(d) The lamp should not be allowed to soot or smoke.
(e) The lamp should not be left unattended in the mine.
(f) The lamp should not be exposed to strong air currents to prevent the flame from "going out".
(g) No combustible material should be ignited by the lamp.

(h) When the flame of a safety lamp indicates a dangerous percentage of gas in the atmosphere to be tested, the lamp should be withdrawn slowly, carefully, and promptly to prevent the flame from going out. If the flame is extinguished suddenly, the lamp should be withdrawn carefully and promptly and should be taken into fresh air and allowed to cool before relighting it.

(iv) Only certified flameproof and intrinsically-safe apparatus should be used. The apparatus should be properly installed, protected, operated, and maintained.

To prevent ignition from electrostatic charges, all ventilation ductings should be earthed and only antistatic hoses and belts used.

A reliable methane cut-out that will automatically cut off power supply to the electrical apparatus when the methane concentration reaches the prescribed maximum value, may be installed in endangered mine workings.

(v) The production of excessive frictional heat with conveyors, brakes, and bearings should be avoided by good installation and proper maintenance.

The production of frictional sparks especially caused by metal-to-rock contact as with cutting, power-loading, and drilling machines should be avoided. The precautionary measures against frictional sparking during cutting of seams consist in selecting an appropriate cutting horizon, wet-cutting, using external sprays directed at the ingoing and outgoing picks or using 'whale jibs' in which the water is piped to a number of points around the apex of the jib, providing a water mist in the cut, introducing inert gas such as carbon dioxide or nitrogen into the cut, or ventilating the cut. Adequate ventilation of the cut using a water spray device or compressed air provides the most effective known means of preventing frictional ignitions.

With power-loading on longwall faces, the frictional ignition hazard varies greatly depending on the type of face power loader used (conventional shearer loader, ranging drum shearer loader, floor- or conveyor-mounted trepanner or trepan shearer loader) and the conditions in which it is operating. Experience in the British mines working thin seams has shown that with good standards of ventilation, the frictional ignitions have been confined to the neighbourhood of the power loader, that the incidence of ignition resulting from picks striking the floor is about twice as great as when picks strike the roof due to the cutting zone at the floor being most difficult to ventilate, and that the risk of ignition is least with the L-shaped outboard arm ranging drum shearer loader and maximum with the single-ended conveyor-mounted trepanner [11].

(vi) Spontaneous heating of coal should be controlled by proper planning of mine development as well as coal extraction, good ventilation system, and inspection.

(vii) Blasting with explosives should be restricted to a minimum. Mechanical winning machines and blasting devices such as Hydrox, Cardox, and Airbreaker Shells may be used as alternatives to ordinary explosives for breaking down coal. Pulsed-infusion short firing in combination with deep-hole water infusion may also be employed for getting coal without machine-cutting.

When blasting with explosives, the following important points; should be observed:

(a) Only "permitted" explosives of the prescribed group or class should be used.

(b) The maximum charge in a hole should not exceed the official or prescribed charge limit.

(c) The length of stemming in a hole should be at least two-thirds the length of the hole and be not less than 60 cm; the stemming should not contain any combustible material. There is probably less danger of ignition of gas in a break that traverses a shothole than with conventional solid stemming and also there is less likelihood of deflagration of explosive in the hole. Water stemming has almost replaced clay and sand stemming in West European mines in which its use is mandatory.

(d) A shot or shots should be fired only when all places within a radius prescribed by mining regulations contain less than the prescribed limit percentage of methane. ;

(e) Blasting should be done only by trained and experienced men who will observe rigid compliance with safety .regulations.

In the U.S.S.R., experiments are at present being conducted on prevention of ignition of firedamp from blasting hi development headings by forming a foam plug at the face by a foam generator just before blasting. The results so far obtained are very encouraging.

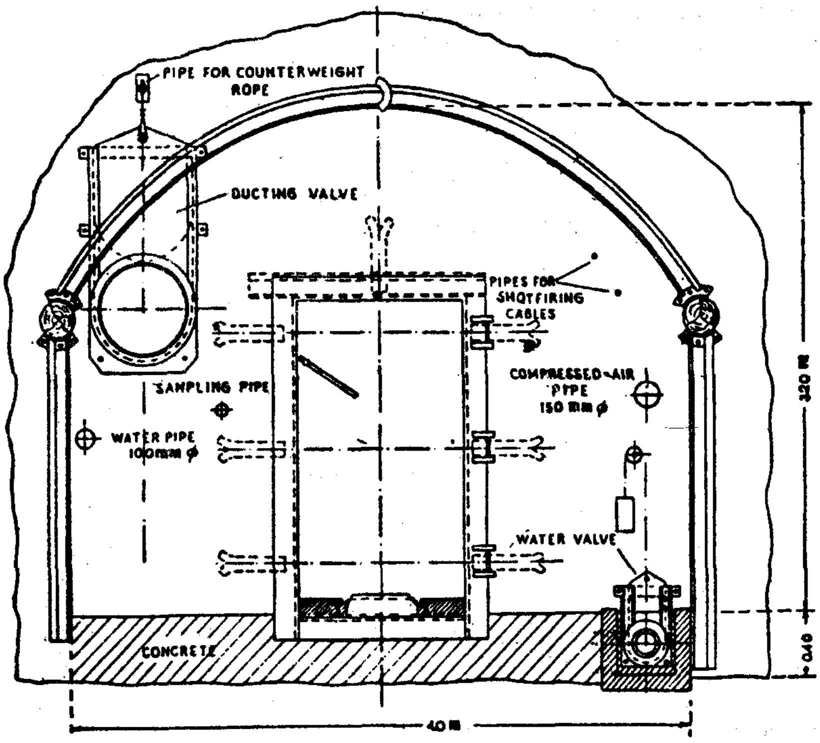


Fig. 43. Blasting Dam ("Schiessdam")

2.1.5.3 Control of Firedamp Emission

In mines where high emissions of firedamp are expected, it is prudent to drain the strata of the gas by means of boreholes at the outset than wait until the methane content of the wastes and the general body of air pose a serious problem.

In seams liable to outbursts of firedamp, special precautions should be observed in their working. Pre-draining at a controlled rate the fire dam and inducer shotfiring are the two most important measures against gas outbursts.

2.1.6 Localization of Firedamp

Explosions

Firedamp explosions may be localized in the following ways:

1) Formation of several ventilation districts by splitting the main intake air-current so that each district has separate intake and return airways.
2) Erecting explosion-proof 'blasting dams' in development heading in gassy mines (Fig. 43).
3) Adopting measures against initiation of coal-dust explosions and their propagation.
4) Maintaining an efficient rescue and recovery organization.

2.2 Coal Dust Explosions

A coal-dust or any industrial-dust explosion is a sudden combustion process of great intensity characterized by mechanical destructive effects through pressure and heat. For an ignition to take place, the combustible dust must be present in the form of a thick cloud having a definite mixing ratio with oxygen, and a source of ignition in the form of flame must be present.

2.2.1 Development of Coat-Dust Explosions

The exact ignition mechanism of flammable coal dust-air mixture is not clear. The view commonly held at present is that surface oxidation of coal dust particles, ignition of flammable mixture of air and gases evolved from partial gasification of solid coal particles and combustion of solid particles are conjointly responsible for the development of a coal-dust explosion. Experience has shown that a coal-dust explosion often develops m stages. The first stage of ignition is often a "puff" which is a sudden combustion of part or whole of air-borne dust marked by a very high temperature but without any dynamic effects. If the whole of the dust is consumed, the combustion of dust-air mixture ends with the puff. On the other hand, if a part of the dust is consumed, the puff may lead eventually to an intense main explosion. During the transition from puff to explosion, there takes place an increase of pressure in the burning layers due to transfer of the heat of combustion to the surrounding unburnt layers mainly by radiation. When the pressure exceeds a certain value, a full-fledged explosion is developed in which the combustion takes place at such a rapid rate (velocity of propagation) that the whole of the heat liberated is transferred without loss to the surrounding unburnt layers. A pressure wave is developed which passes through the unburnt layers ahead of the explosion does not depend any more upon the presence of a flammable dust-air mixture but the pressure wave will itself stir up the deposited dust creating necessary fuel in the form of a pioneering cloud for the following flame.

When the rate of propagation of an explosion assumes greatest values, the ignition of a dust-air mixture takes place just at the instant of the arrival of the pressure wave at it and the explosion assumes the character of detonation. In practice, however. Just explosions do not develop into-detonations, being governed by the amount of dust and the characteristics of dust-air mixtures.

2.2.2 Flammable or Explosive Limits

Flammable or explosiveness of a dust is defined as its ability when in the form of a cloud to spread ignition to all points where dust-air mixtures of corresponding concentration are present. Sometimes a distinction is drawn between the terms "flammability" and "explosibility" of a dust, the difference lying in the so called explosible dust to produce violent or destructive effects. Such hard and fast distinction is really difficult to maintain as the factors affecting flammability and explosibility of dust-air mixtures are same and also it is difficult to say when a puff would become an explosion.

Like firedamp-air mixture, a coaldust-air mixture has lower and upper limits of flammability but the range of flammability is very wide, much wider than in the case of firedamp mixture.

The lower limit is not an absolute quantity. It depends on the particle size and chemical composition of dust, nature and intensity of the igniting source, time of contact with the source, uniformity of dispersion, purity of the sample, and the composition of the atmosphere especially the methane and oxygen contents. Bituminous coals have a lower limit of flammability of 30 to 70g/Nm^3 air volume. At the lower limit, the dust cloud obscures a cap lamp at a distance of 3.5 m.

The upper limit of flammability is indefinite because of the difficulty of maintaining dust clouds of high concentrations and is unlikely ever to be reached under mining conditions. For bituminous coals, the upper limit lies above 2000 g/Nm^3.

As with firedamp mixtures, explosions of limit dust-air mixtures are weak. Curves obtained by plotting explosion pressures against concentrations show that maximum rates of pressure rise and maximum explosion pressures are lowest at the lower limit and that they gradually increase until the optimum concentration is reached after which they decrease with further increase in concentration. The most violent explosions are produced when the concentration of coal dust is about ten times the lower limit (400 to 500 g/Nm^3), although for complete- combustion only-413 g/Nm^3 (pure carbon) would be sufficient. With dust concentrations greater than the optimum, absorption of heat by the unburnt dust is apparently the reason for less than maximum pressures.

2.2.3 Ignition of Coal Dust-Air Mixtures

Ignition of dust-air mixtures is not so readily brought about as with gas-air mixtures. In general, a rather larger source of heat is required. The ignition temperature (ignition range) depends on the type of coal, nature and intensity of source of ignition, particle size, moisture and ash contents, and oxygen concentration. Moisture in dust particles and in the surrounding atmosphere raises the ignition temperature of the dust because of the heat absorbed for vaporization and heating of the moisture. With decrease in oxygen concentration, the energy required for ignition increases and the ignition temperature increases. The minimum spark energy required for ignition of dust clouds of different coals lies between 40 and 120 mJ. For dry dusts of different coals, the ignition temperatures lie between 602 and 900°C.

2.2.4 Ignitibility of Dust

Ignitibility of a dust is defined as the ease with which its ignition, when in the form of a cloud, spreads throughout the cloud with or without dynamic effects. The factors affecting it are the same as those which influence its flammability or explosibility.

The relative ignitibility of dusts of coals can be determined by one of the following methods:

1) Measuring the distances to which the explosion flame spreads throughout the dust clouds of the coals.

2) Measuring the rates of propagation of the flame through the dust clouds.

3) Determining the relative amounts of incombustible dust required to prevent flame propagation in the dust clouds.

2.2.5. Factors Affecting Explosibility of Coal Dusts

The explosibility of coal dusts has been the subject of many investigations in laboratories and experimental coal mines on the origin, propagation, and control of coal-dust explosions. It was learnt tint the degree of explosibility of dust deposited in mine workings as measured by" the proportion of inert dust required to be added to render it nonexplosible, varies within wide limits.

The following physical and chemical factors exercise an important influence on the explosibility of coal dust and control of coal-dust explosions-in mines.

1) Fineness of Dust (Particle Sire)

It has been found from investigations that coal dust particles up to 0.75 to 1 mm size [18] take part in explosions but that fine particles control the ease of ignition, the violence, and the speed of flame propagation. Dangerous-are the particles which lie between 10 and 100-micron size. The loss of 3 certain degree of explosibility of dust below 10-tnicron size is explained as due to chemical decomposition of dust at that degree of fineness, tendency to agglomerate, and rapid oxidation on initial exposure to air becoming less easily ignitable.

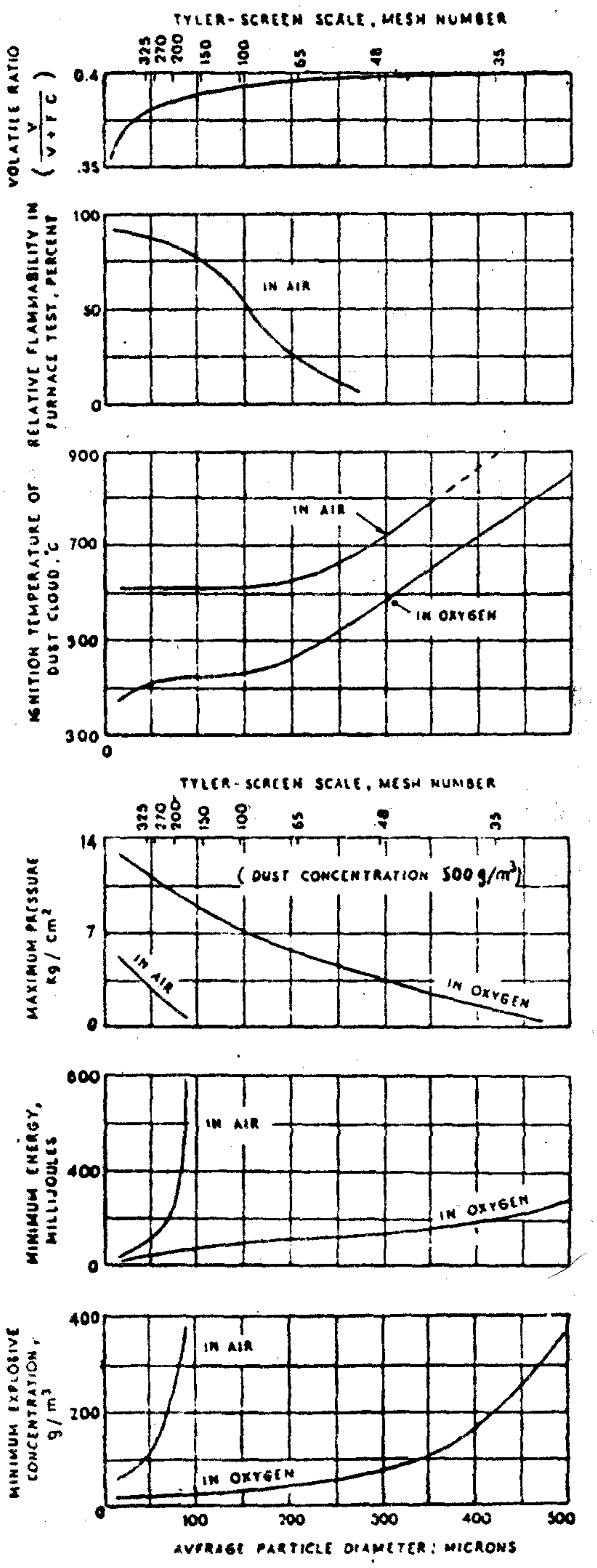


Fig. 44. Effect of Particle Size on Minimum Explosive Concentration, Minimum Igniting Energy. Pressure Development, Relative Flammability and-Volatile Ratio of Piitsburg Coal Dust Clouds in Air and in Oxygen.

Fig. 44 shows the effect of particle size on the lower explosive limit, minimum ignition energy, maximum pressures, ignition temperature, relative explosibility, and volatile ratio of bituminous Pittsburgh coals [23]. Fig. 45 shows the effect of various proportions of through 200 mesh dust on the explosibility of the same coals.

2) Percentage of Volatile Matter

The explosibility of a coal dust depends greatly on its combustible volatile matter: it increases with increasing volatile content. The volatile matter is usually calculated on pure coal basis by the formula

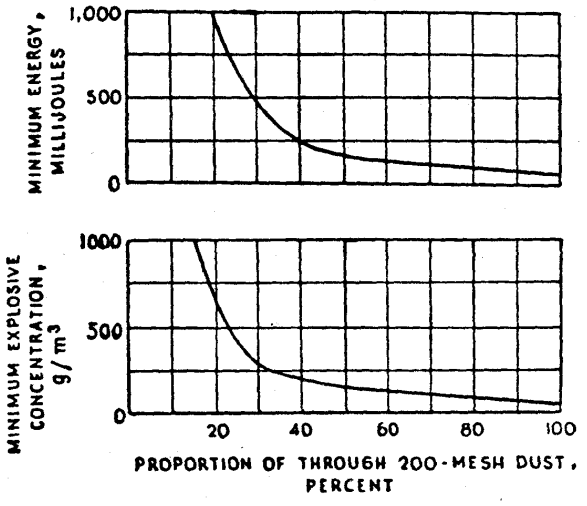


Fig. 45. Effect of Various Proportions of Through-200-Mesh particles on Minimum Explosive Concentration and Minimum Igniting Energy of Pittsburg Coal Dust Clouds in Air

% VM = (%VM (from analysis) x 100) / 100 - % ash - % moisture

As the -right-hand side of the above formula may be written as

= (% VM) / % VM + % FC.

the percentage of volatile matter on pure coal basis is sometimes called volatile-combustible ratio or simply volatile ratio of coal.

Several investigations in laboratories, surface experimental galleries, and experimental mines on the explosibility of coal dusts have shown that coal dusts with VM < 10% are non-explosible, those with VM =10 to 14% are less explosible whilst those with VM>14% are highly explosible and dangerous. The increase in explosibility, however, is different for different coals. Fig. 46 shows the variation of explosibility with volatile ratio of mine-size dusts of bituminous Pittsburgh coals as determined by laboratory and experimental mine tests [23]. For low-volatile coals, the explosibility increases almost linearly with increase in VM but above about 25% VA in the range of medium and high-volatile bituminous coals, the explosibility rises only slightly with increase in VM.

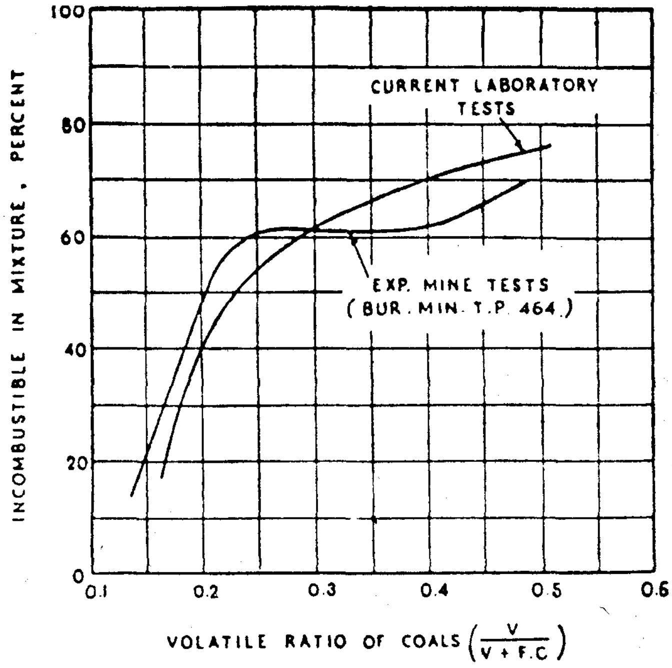


Fig. 46 Variation of Explosibility with Volatile Ratio of American Coals.

Fig. 47 shows the effect of volatile matter on the lower explosive limit, minimum ignition energy, and ignition temperature of coal dusts [23].

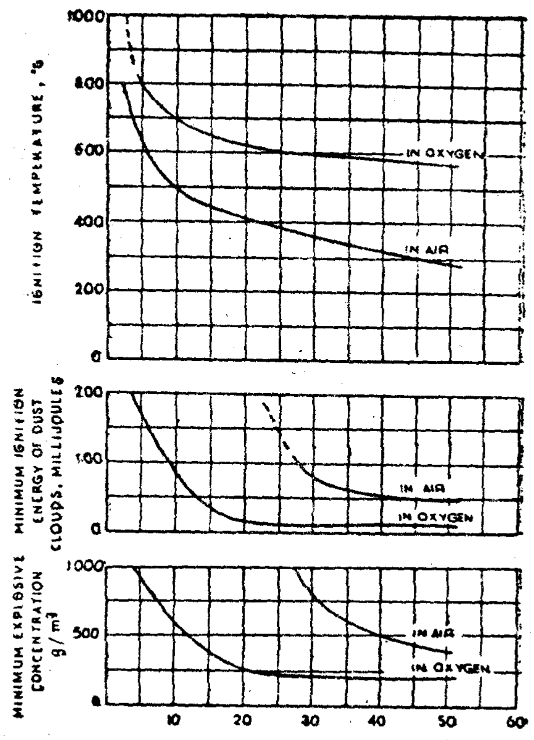


Fig. 47. Effect of Volatile Matter on Lower Explosive limit, Minimum Ignition Energy, and Ignition Temperature of Pittsburg Coal Dust Clouds.

3) Percentage of Ash

Increase in the ash content or presence of inert foreign material reduces the explosibility of coal dust which becomes less readily ignitable because of heat absorption.

4) Percentage of Moisture

Moisture reduces the explosibility of the coal dust. It has a cooling effect because heat is needed to vaporize it, reducing the energy available for the ignition of the dust cloud. It also tends to wet and agglomerate the fine particles of dust reducing their dispersability Coal dust loses, its dispersability with a moisture content of 25 to 30%. The effect of moisture on explosibility is unimportant below about 10%.

5) Chemical Composition of the Volatile matter and the gasifying capacity of the Dust.

The chemical composition of the volatile matter and the, gasifying: capacity of a dust exercises a great influence upon its explosibility. Greater the quantity of the combustible gasification products liberated at lower temperatures, greater is the explosibility of the dust.

6) Dustiness of the Mine Workings

The quantity of the deposited dust *is expressed it* g/m^3 of- mine excavation and the density of a dust cloud in g/Nm^3 of air.

The determination of the lowest limit of the deposited dust in a mine, working at which an explosion can occur is very difficult as the whole of the dust need not necessarily be suspended in air for an ignition to take place. From experiments conducted in experimental mines [18J, it had been found that a mine working is dangerously dusty if it contains 100-120 g/m^3 and that the most violent explosion occurs at 300-400 g/m^3.

The minimum density of a dust cloud which will propagate an explosion depends on the nature of the source of ignition, fineness of the dust, rank of coal, and other parameters. It is determined to be of the order of 30 g/Nm^3. The dust cloud must be dense at the point of ignition so that

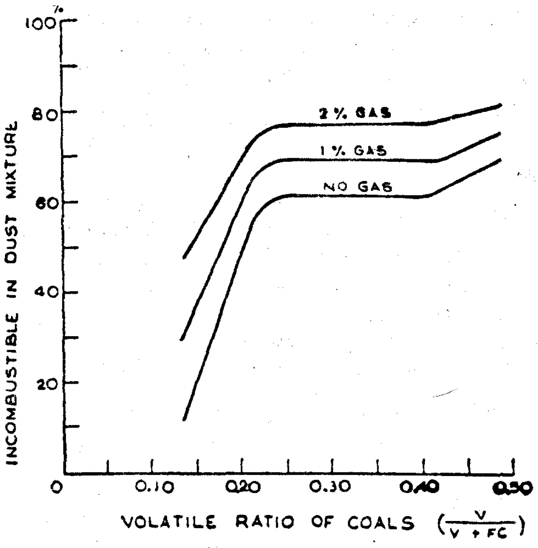


Fig. 48. Effect of Firedamp on Explosibility of Coal Dust Clouds.

one cannot see through it. It should not, however, be inferred from this that the dust cloud must be large but that it must only be dense immediately surrounding the igniting source. As the airborne dust concentration in mine air currents is not sufficient to propagate an explosion, the explosion must stir up the deposited dust along its path to create a cloud for its propagation.

7) Percentage of Firedamp in Mine Air

The presence of firedamp in mine air in percentages less than its own lower limit reduces the lower explosive limit of coal dust by replacing the coal on a weight-thermal basis. 1% CH_4 (by volume) in 1 m^3 of air is equivalent to about 12 g of coal dust. The explosibility of coal dust increases almost directly in proportion to the percentage of firedamp (Fig. 48) [24].

8) Oxygen Concentration

Variations in *oxygen* concentrations affect the ease of ignition of dust clouds and the explosion pressures.

9) Nature and Intensity of ignition Source

The nature and intensity of the igniting source (temperature, size of spark or flame etc) exert great influence on the explosibility of the mine dust under mining conditions as they determine the dust-dispersing capacity and the turbulence induced within the dust cloud. Explosions initiated by strong sources develop faster and cause more damage than explosions initiated by weak sources.

10) Distribution of Dust in Mine Workings

The varying conditions of distribution of dust along the length and perimeter of mine workings affect the propagation of a dust explosion. Dust deposited on the floor constitutes less explosion hazard than dust on the sides and roof and on overhead bars. The former is usually diluted by shale, sand or other impurities and is relatively coarser than the latter.

11) Surrounding Conditions

The size, shape, constrictions, obstructions, branching, length nature and condition of the surfaces of mine workings exert an important influence on the development of coal-dust explosions.

2.2.6 Coal-Dust Explosion Characteristics

2.2.6.1 Flame Temperature

Maximum flame temperatures occur at stoichiometric concentrations. The theoretical flame temperature for stoichiometric mixtures is about at constant volume). In practice, the temperatures obtained lie between.800 and 1000°C [25].

2.2.6.2 Explosion Pressure

The maximum explosion pressures obtained experimentally for dusts-of different coals lie between 3.2 and 6.7 atg [11]. They depend on rank of coal, particle size, concentration, initial pressure, and turbulence. The dynamic pressures encountered are of the order of 1 atg [26]

The rate of pressure rise is the ratio of the increase in explosion pressure to the time interval during which energy is leased. The maximum rate of pressure rise is obtained as the steepest slope of the pressure-time curve. The destructiveness of a dust explosion depends primarily upon the rate of pressure rise. The rates of pressure rise are, however, less than with gas explosions.

2.2.6.3 Rate of Propagation of Explosion Flame or Flame Velocity

Velocities of propagation of explosion flame up to 1000 m/s or more (usually 200 to 300 m/s) are encountered in mines. In a roadway of constant cross section which - is more or less uniformly dusty, the velocity of flame propagation and explosion pressure increase with the distance from the seat of the explosion. The velocity is greatly affected by sudden variations in cross-section of mine workings through which the explosion passes, the amount of dispersed, stone dust, and pressure release into adjacent areas,

2.2.6.4 Explosion Gases

As the oxygen of the mine air is nearly always not enough or combustion of all the dust present in mine workings, carbon monoxide is always found in the explosion gases m concentrations up to as high as 14%. The toil of lives taken by a; coal-dust explosion is not merely due to the effects of die explosion flame or force but due mainly to breathing of the poisonous carbon monoxide gas.

2.2.6.3 Destructiveness

A coal-dust explosion usually destroys completely and quickly whatever objects are present in its way. Its pressure wave radiates intense heat which can melt metals and convert organic matter into coke and ash. Its destructiveness depends upon the maximum, explosion pressure, rate of pressure rise, duration of excess pressure, and confinement.

2.2.6.6. Formation of Coke Crust and Soot Deposits

In a coal-dust explosion, only a part of the dust is completely burnt into ash whilst the remaining dust gets coked and deposited as characteristic crust or globules on roadway supports and on the sides and roof of the roadways through which the explosion passes. The presence of visible traces of coke crust after an explosion depends on the caking properties of the coal Bituminous coal yield larger coke crusts than non-caking coals which yield granular crusts. Experience with large explosions in mines has often shown that the coke crust is invariably formed- on the reverse or sheltered side of the roadway supports or projection (Fig. 49) add that it is found on the "windward" side of the supports or projections near the seat of the explosion. In small explosions with less flame velocities, in- the other hand, the coke crust is found on all sides of die supports. Experiments in the U.S. Bureau of Mines experimental coal mine (27]" showed that explosion flame can traverse an area without producing coke and that as the explosion flame velocity increases, the amount of coke produced decreases.

Soot is deposited in and beyond the area traversed by the explosion flame. Soot deposits are generally thicker in the explosion area. Soot may be deposited as a continuous layer on horizontal surfaces or form lacy network or stringers at the roof and on vertical surfaces.

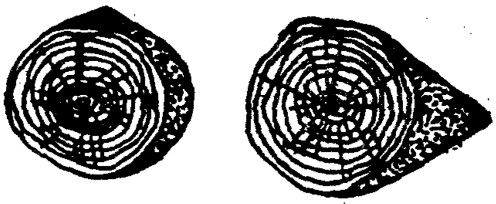


Fig. 49. Coke Crust on Bars and Props.

2.2.7. Comparison of Coal Dust and Firedamp

Coal dust and firedamp have many common properties besides- their characteristic features.

1) Both have lower and upper limits of flammability. Explosions of limit mixtures are weak.

2) The ignition temperature of firedamp is 650°C to 750°C while that of dry airborne coal dust airborne coal dust 600 to 900°C.

3) The heats of combustion and explosion temperatures are nearly same.

4) The flammability of firedamp is generally the same throughout the mine. On the other hand, the ignition and flammability of dust in mine workings vary greatly depending on fineness, volatile matter, ash, moisture etc.

5) The propagation of firedamp explosions 'takes place due to conduction of heat. With coal-dust explosions, on the other hand, radiation of intense heat by the pressure wave as well as the explosion flame plays an important-part in their propagation.

6) The maximum pressures developed in some dust explosions are higher than in firedamp explosions. The rates of pressure rise are, however, generally lower than those obtained with firedamp explosions.

7) Coal-dust explosions are frequently more disastrous in their effects than firedamp explosions because of their longer duration.

8) With firedamp explosions, carbon monoxide is frequently found. With coal-dust explosion, on the other hand, carbon monoxide is always found.

9) The initiation of a coal-dust explosion, even with the strongest igniting source requires at least 100 ms while with a firedamp explosion only 1 to 2 ms are required [26].

10) The velocity of propagation of coal-dust explosions is generally higher than that of firedamp explosions.

2.2.8 Dust Explosion Test Apparatus

Various types of apparatus for measuring dust explosion properties have been described in the literature on dust explosions.

Ignition Temperature

The apparatus developed by the U.S. Bureau of mines consists essentially of an electrically-heated vertical cylindrical tube through which a weighed amount of coal dust is projected downward as a uniform cloud by a controlled blast of compressed air directed at the dust sample placed in a small container at top of the tube. The lowest temperature at which flame issues out of the open bottom end of the tube gives the ignition temperature. This apparatus may also be used for determining the inert dust limits for different coal dusts. Fig 50 gives the diagrammatic arrangement of Godbert-Greenwald apparatus for determining the ignition temperature and relative flammability of dust clouds [28].

The Russian (Stepanow) and the German apparatus differ from the Bureau of Mines apparatus mainly in that a horizontal furnace is used instead of a vertical one.

Minimum ignition Energy

The apparatus developed by the US. Bureau of Mines [12] consists of a vertical cylindrical lucite tube in which dust is dispersed upward-as a cloud by controlled discharge of compressed air into the dust "sample at the bottom of the tube. A spark discharged by an electrical condenser synchronized with the formation of the dust cloud is used as the igniting source and by using condensers with different capacities, the spark energy can be varied. Visible flame in the tube signifies ignition of the dust cloud.

Explosion Pressure and Rate of Pressure Rise

The apparatus developed by the U.S. Bureau 01 Mines [12] *toe-*

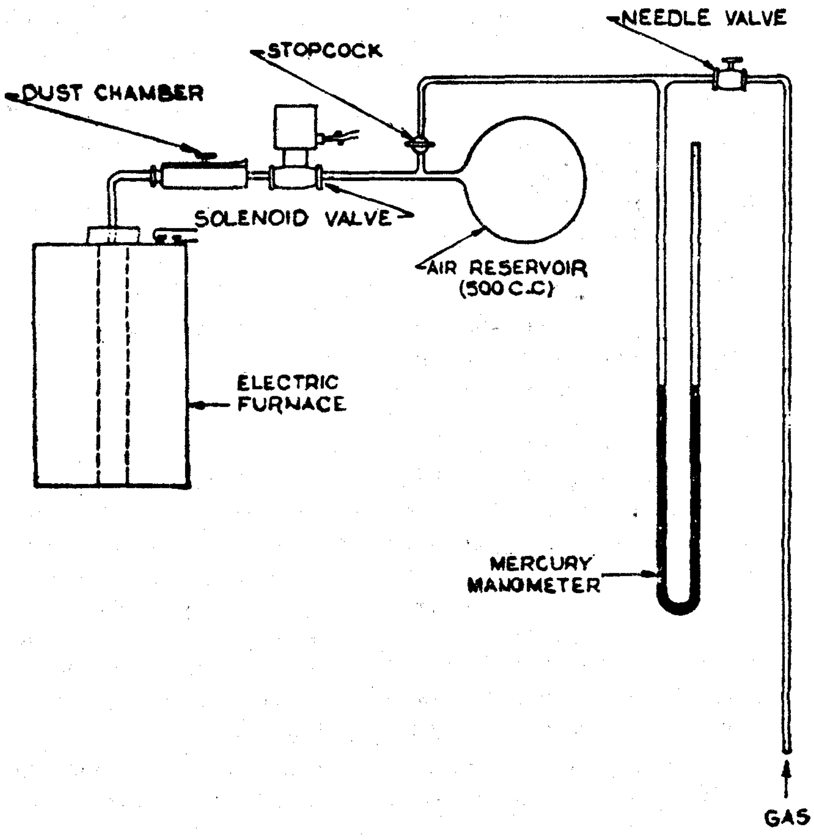


Fig. 50. Godbert-Greenwald Apparatus for Determining Ignition Temperature and Relative Flammability of Dust Cloud.

determining maximum explosion pressure' and rate of "pressure rise' consists of a vertical cylindrical steel-bomb into which a weighed sample of dust can be dispersed upward by a jet of compressed air.

The pressures developed are measured by a diaphragm-type manometer mounted above the bomb, A pressure-time record of the explosion is obtained by photographing an intervals of 1/120 second the deflection of the diaphragm.

The German apparatus (German Materials Testing Establishment) [29] is similar to the Bureau of Mines apparatus. A spark discharged by an electrical condenser is used as the igniting source and a pressure-time record of the explosion is obtained by mechanical or electronic recording apparatus.

2.2.9 Causes of Coal-Dust Explosions in Mines

In practice, the causes that bring about ignition of explosive dust-air mixtures are very similar to those operating in the ignition of flammable firedamp mixtures but the ignition hazard, in general, is rather greater as coal dust is the normal accompaniment of the coal winning process and can be easily raised into the mine air. For a coal-dust explosion to take place in mines, two conditions must be fulfilled: the dust must be present as a thick cloud, and a source of igniting energy in the form of flame must be present.

The various causes of direct ignition of dust clouds can be classified as under:

Naked flames
Friction
Electric sparks
Firedamp explosions

2.2.9.1 Naked Flames

A naked flame is the easiest means of igniting a dust cloud as the source of heat is of considerable size and a larger part of the dust cloud can be heated.

2.2.9.2 Friction

Hot surfaces as a result of mechanical friction, such as overheated, bearings may ignite surrounding explosive dusty atmospheres. ;

12.9.3 Electric Sparks

Electric sparks from short-circuiting and arcing at electrical equipment may ignite an explosive dust-air mixture. Sparks of higher voltage and amperage are usually necessary than in the case of flammable firedamp mixtures.

Static electric sparks can also ignite explosive dust-air mixtures. Fine particles of dust may readily become electrified by friction with air or ducting through which they pass. As the electric charge on a body resides on its surface, a dust cloud has a very large capacity. Under suitable conditions a discharge or sudden recombination of separated positive and negative charges can occur which can act as a source of ignition. With increasing humidity, the electric potential, however, falls.

2.2.9.4 Firedamp Explosions

A firedamp explosion is the commonest source of initiation of a- coal-dust explosion. Besides posing the danger of such direct ignition, a firedamp explosion may raise the deposited dust into mine air very quickly before its flame has ceased and then propagate as a coal-dust explosion. A very small gas explosion may thus bring about a much bigger coal-dust explosion. This danger is particularly great in long headings than in long coal faces due to low air velocities and lack of adequate pressure relief except in one direction towards the entrance of the heading. It is significant that most firedamp explosions do not develop into coal-dust explosions due to their failure to raise a sufficient dust cloud.

2.2.10 Prevention and Suppression of Coal-Dust Explosions

It is a well-known fact that it is much easier to prevent a coal-dust explosion being initiated than arrest one.

The measures of prevention and suppression of coal-dust explosions can be divided into the following three groups:—

2.2.10.1 Measures which Presents or Reduce Formation and Dissemination of Coal Dust Underground

The elimination of coal dust in mines would be a logical means of eliminating the coal-dust explosion hazard, but unfortunately, this is virtually impossible. Much can, however, be done to reduce the formation, distribution, and accumulation of dust in mine workings.

The following important measures should be adopted:

(i) Water infusion of the coal face at normal (5-20 atg) or high (80-250 atg and above) water pressures where the seam and adjacent strata allow [Fig. 51]. The effectiveness of coal face infusion depends on the amount of water injected and its uniform distribution in coal. The amount of water required lies between 8 and 10 litres per solid cubic metre coal.

(ii) 'Wet winning' of coal using wet pneumatic picks.

(iii) With machine-cutting, using sharp picks of suitable type, selecting optimal cutting and travelling speeds of the machine, using gummer, and wet-cutting.

(iv) With power loading, using the conventional shearer loaders, by using sharp picks of suitable type and pick lacing, selecting suitable drum design, optimal rotational speed of drum, travelling speed of the machine, and proper direction of drum rotation ; introducing water to the pick clearance line through hollow drum shaft by having sprays in the barrel or mounted on the vanes; flushing the cutting edges of the picks from jets located cither in or close to the pick boxes (pick face flushing), using external water sprays.

Internal water sprays with a water pressure greater than 15 kg/cm^2 have beer, found to be more effective than external water sprays.

(v) Wetting thorough coal pile before it is manually or mechanically loaded.

(iv) Using such types of conveyors with which the dust production is minimum.

(vii) Water spraying transfer and loading points and improving their design.

(viii) Preventing spillage and degradation of coal during transport in roadways by

(a) using undamaged dust-tight cars,

(b) avoiding overloading so that it will not spill in transit,

(c) Water spraying the full and empty trains during their transport (Fig. 52), and

(d) Maintaining the haulage track in good condition, and

(e) On coal conveyor roadways, reducing spillage by selecting suitable capacity of conveyor as well as proper belt width and speed, providing adequate bunker capacity at loading points, and centralizing the flow of coal.

(ix) Restricting velocities of air currents in mine airways to less than 3m/s.

(x) Preventing dust accumulation in mine workings by

(a) Dry suction at loading and unloading points at which large Quantities of dust are produced which cannot be suppressed in the ordinary way.

(b) Cleaning systematically and regularly main haulage roads and main return airways of dust (3 to 4 times a year) by transportable roadway suction apparatus.

(c) Installing skip hoisting in up cast shafts, and

(d) Locating dry coal preparation plants far away from downcast shafts (not less than 80 m).

(xi) Selecting a method of winning with, which the dust production is least.

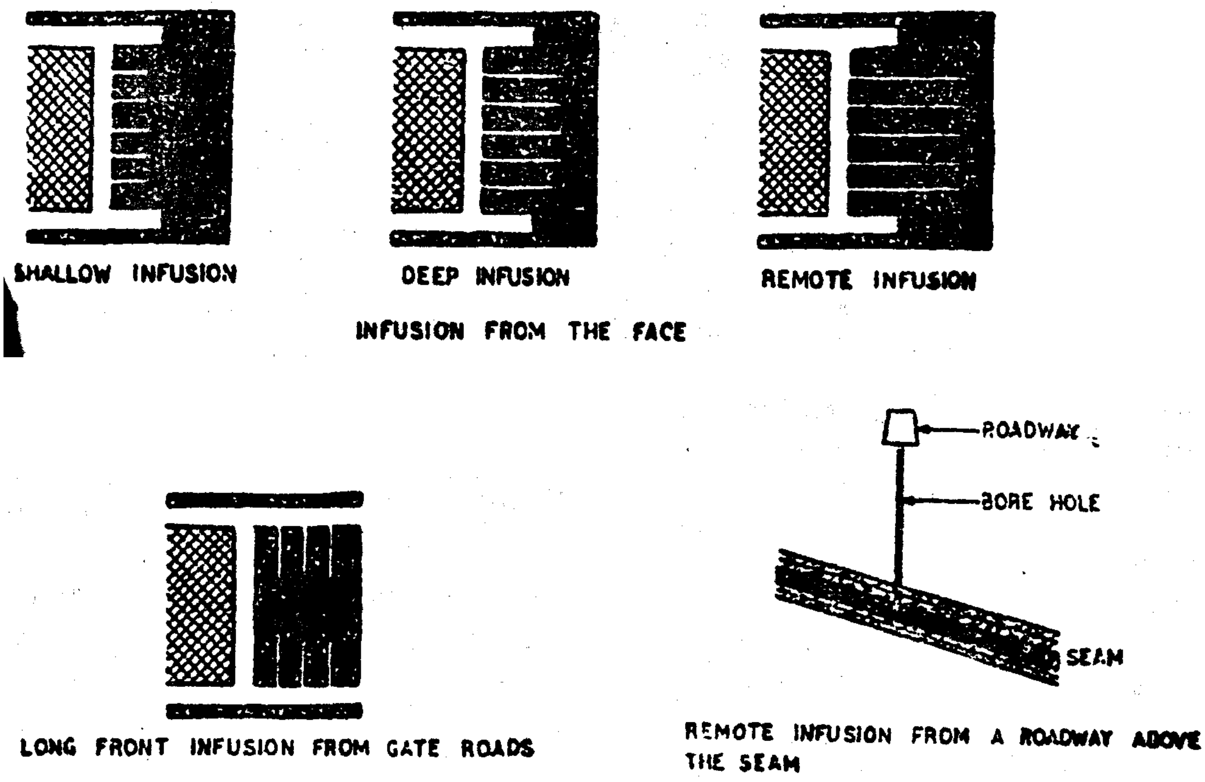


Fig 51. Method of water Infusion of a Longwall face.

2.2.10.2 Measures against Ignition of Dust Accumulations

These measures comprise:

(i) Measures against ignition of flammable firedamp mixtures.

(ii) Neutralization or consolidation of dust at working coal faces within a radius of 10 to 20 m before shotfiring by means of inert water or stone dust,

(iii) Neutralization of dust in roadways by means of water, stone dust, and hygroscopic salts.

2.2.10.3 Measures against Explosion Propagation

Dustless zone in mine workings might at first seem to be logical means of arresting a coal-dust explosion. But experience has shown that strong explosions can easily propagate through several hundred metres of nearly dust-free zones due to burning dust being transported in the moving air column.

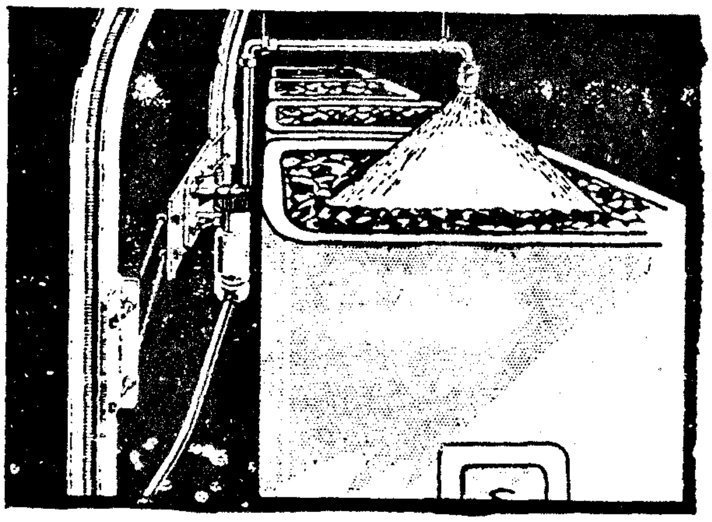


Fig. 52

Fig. 52. Automatic Water Spraying of Full Trains.

The protective measures which have been found in practice to have varying degrees of effectiveness in arresting explosion propagation are:

Generalized wetting of coal dust
Generalized stone-dusting
Stone dust barriers
Explosion stoppings
Salt zones
Water barriers
Triggered barriers

2.2.10.3.1 Generalized Wetting of Coal Dust

Wetting of coal dust as an effective means of arresting propagation of coal-dust explosions in dry mine workings was known ever since the explosion hazard of coal dust was recognised. For water to be effective it must be present in sufficient quantity and be mixed intimately with coal dust. The percentage of admixed water (by weight) required to prevent propagation of a coal-dust explosion depends on the fineness of the dust, strength of the igniting source, volatile content of coal, and amount of stone dust .present. It should not be less than 50%. In practice, coal dust is wetted by washing excessive deposits of it on the side and roof surfaces to the floor by means of hoses, thereby converting the dust into mud. To increase the wettability of coal dust which neither absorbs nor absorbs water readily, a wetting agent may be added to the water. The disadvantages of water as an inert for neutralizing the coal-dust explosion hazard are:

(a) Wetting must be done continuously by streams of water which must be available in sufficient quantity

(b) Relative humidity of mine atmosphere is increased

(c) Heaving of floor, if soft, occurs

(d) Cost of the plant is high as the entire mine workings must be equipped with water mains.

2.2.10.3.2 Generalized Stone-dusting

The British engineer W. Garforth first observed in the year 1891 that an explosion did not propagate to a part of a mine which was well stone dusted. With this observation began stone dusting in Britain which began officially adopted stone dusting in 1920. It was after the greatest explosion of all times that occurred in the year 1907 in Courriere mine in France that French scientists and engineers notably M.J. Taffanel and a German engineer Beyling engaged themselves with stone dusting. Stone dusting was officially adopted in France in 1911 and in Germany in 1926. Today generalised stone dusting is done in mines of almost all coal mining countries of the world.

Generalised stone dusting consists in applying stone dust on the sides, roof and floor of all mine workings except those within 10mts or less of all working faces so that it overlays the deposited coal dust and thus prevents the latter from being ignited or taking part in an explosion. If a mine or any part of it is naturally ‘too wet’ (condition where in water exudes if a ball of dust is squeezed in the hands) or too high in incombustible content to propagate an explosion, stone dusting is not required in that mine or part.

The value of stone-dust application is due to the following facts:

(a) When coal dust is mixed with enough incombustible dust, it will not explode or assist in propagation of an explosion.

(b) When incombustible dust is raised into an explosion fume in a sufficiently dense cloud, it gets heated up taking away heat from the flame. This cooling effect is greater, greater the amount of stone dust is in the flame. In the case of coal-dust explosions, the incombustible dust also serves to shield or blanket the coal dust particles from heat of radiation so that they do not take part m combustion any more, and also hinder diffusion of oxygen and gases into and from the burning coal particles

Table 1 Stone-dusting Requirements in some Coal-mining Countries [30]

Country	% Incombustible Content minimum.		Remarks.
Austria	1959	0	All roads are wetted
Belgium	1965	60-78	VM 14% to more than 26%
Canada	1959	65	Add 1% for each 0.1% CH4
Czechoslovakia	1957	80	
France	1965	50-70	VM less than 22% to more than 29%
F. R. Germany	1965	80	Unless treated with paste
Holland	1965	65-80	For CH« from 0-1.5%
India	1957	70	
Poland	1959	70-80	Nongassy - gassy
U.K.	1961	50-75	VM up to 20-35% and above
U.S.A. (Fed.)	1960	65	Add 1% for each 0.1% CH4
U.S.S.R.	1953	60-75	Non-gassy - gassy.

As coal dust is constantly produced as a result of mining operations and gets deposited by ventilating contents in mine workings, one application of stone dust will not suffice to keep the mine workings immune from explosions. Stone-dusting must be applied at regular intervals of time after it has been first applied.

On the basis of tests carried out in surface experimental galleries, different countries have prescribed different minimum percentages of incombustible matter in the combined coal dust, stone dust, and other dusts on the floor, roof and sides of mine roadways at all times. Table 1 gives the stone dusting requirements in some coalmining countries of the world f30]. The minimum percentage of incombustible content required of mine' dust depends on the character of coal especially its volatile content on ash-free dry basis, fineness of the dust, and the percentage of methane present in the mine atmosphere. Where methane is present in any ventilating current, it is recommended that the minimum percentage of incombustible content of such dust be increased by 1% for each 0.1% of methane [24]

For a given coal, the quantity of stone dust to be applied in mine workings can be calculated from the following relation:

$$\frac{0.01\,a + x}{1 + x} = \frac{b}{100}$$

where

x is the quantity of stone dust required (kg/kg of combined mine dust)

a is the percentage of incombustible matter already present in the combined mine dust

b is the prescribed minimum percentage of incombustible content About 3 to 7 kg stone dust per tonne of coal output will be required.

2.2.10.3.2.1 Characteristics of Suitable Stone dust

All stone dust used for stone-dusting and other purposes in mine must fulfil certain requirements in respect of fineness, dispersability, combustible matter, and effect on health. Different countries have prescribed different specifications for a suitable stone dust (Table 2).

Table 2: Specifications of stone dust in some coal mining Countries

	Fed. Republic of Germany	U.S.A.	U.S.S.R.	U.K.	India
Fineness	100% through sieve 144 mesh/cm^2 and at least 5% through sieve 6400 mesh/cm^2 by weight.	100% through 20-mesh sieve and at least 70% through 200-mesh sieve, by weight.	Same as in Fed. Republic of Germany.	100% through BS 60-mesh sieve roughly below 250 ft and at least 75% through 240-mesh sieve roughly below 66 ft , by weight	Not specified
Combustible matter	<3%	<5%	<5%	Not specified	
Total silica content	<10% by weight in fraction < 20 µ 5% in the respirable fraction < 5µ	5% by weight	10% by weight	Not specified	No free silica

A suitable stone dust should not be hygroscopic so that it does not cake when not directly wetted by water from the strata. It should be readily dispersible into the air when blown by the mouth or by a suitable appliance, and be soluble in the fluids of the lungs. It should also be as light in colour as possible, preferably white.

The standard stone dust is prepared in special mills out of clayey shale, dolomite, gypsum or limestone. From tests conducted in an experimental gallery in the U.K. [31] on the relative efficacies of shale, limestone, and gypsum dusts, it was found that gypsum dust is the most effective of all showing more than twice the efficacy of shale dust and nearly twice that of limestone dusts. Owing to its cheapness, easy availability, white colour, low silica content and little tendency to cake. Limestone dust is, however, the most commonly used in mines throughout the world.

2.2.10.3.2.2. Stone dust Application

Where stone-dusting is done, it should be done in such a manner and at such intervals of time as will ensure that the mine dust on the floor, roof and sides throughout will always consists of a mixture containing not less than the prescribed percentage of incombustible matter. Excessive or blanket stone-dusting of the floor of mine workings can never compensate for deficiency of stone dust on the sides and roof.

Before applying stone dust in mine workings for the first time, all excessive coal dust, loose coal and other combustible material should be loaded out as far as possible. This reduces the required amount of stone dust and facilitates mixing of the stone dust with the coal dust. Stone-dusting should begin in the active sections of the mine where explosions would be most likely to originate (within 10 m of active coal faces) and advance outward to the shafts as well as inbye as the workings advance.

Stone dust can be applied by hand or by mechanical means using stone-dusting machines.

Hand-dusting by broadcasting with hand scoops is cumbersome, has low capacity, and in consequence, is not suitable for large or mechanized mines. A man can stone dust 15 to 20 m of a roadway 9 to H *m*- in cross-section per shift [18]. In machine-dusted mines, hand dusting is confined to within two cuts of a face.

Mechanical dusting is idle for large and mechanized mines as it is the most economical, efficient and rapid method. The stone-dusting machines or stone dust distributors below fluidized dust on to mine surfaces through tubing *or* hose which may be up to 200 m long. They have high capacities so that a considerable amount of dust can be applied in a very short time when an opportunity offers. Both low-pressure and high-pressure machines are available in the market. The low-pressure machines are portable machines which can be moved from one face to another for face-area stone-dusting as soon as the face is loaded out. The high-pressure machines have dust capacities up to one tonne per minute and are used for applying dust in intake haulage roadways and return airways as well as to face-areas. The well-known machines are those manufactured by the Mine Safety Appliances Co., Pittsburg, U.S.A., and the American Mine Door Co., Ohio, U.S.A. They are equipped with 5 to 20 h.p. electric motors and are available as skid, track, or rubber tyre-mounted units (Fig. 53a and 53b).

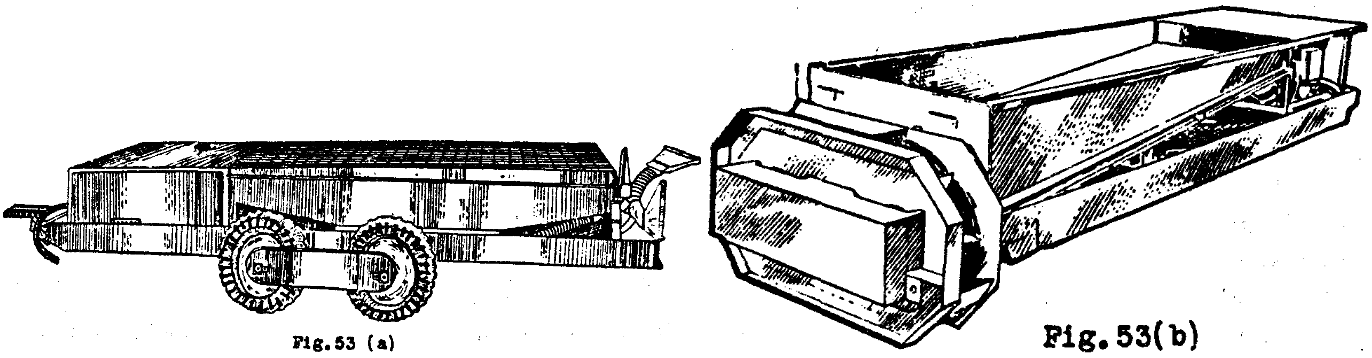
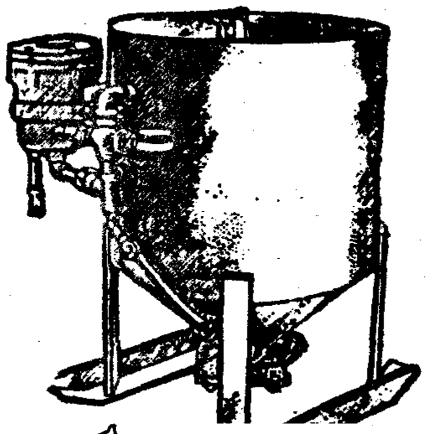


Fig.53 (a)

Fig.53(b)

Fig. Stone dusting Machines, (a) M.S.A. SC Rock dust Distributor, (b) "Canton" Air-flow Dock Duster.

Their minimum heights are 400 mm on skids, 558 mm on rubber tyres, and 635 mm above rail on wheels. The skid-mounted machines may be mounted on shuttle cars, belts or mine cars. The tyre and track-mounted units may be of portable, mobile, or towed-type. Experience has shown that the tyre-mounted unit towed by a battery-operated tractor provides maximum flexibility, manoeuvrability, and range. In mine workings containing compressed air pipe ranges, compressed air operated tank-type dusting machines may also be employed (Fig. 53c).



Mechanical dusting should be carried out only when the workplaces to which the dust is carried by ventilating current are free of workmen.

Auxiliary exhaust fans when used to improve ventilation can also be utilized for stone-dusting by introducing dust at the fan discharge.

In mines with extensive mine workings where the handling and distribution of bagged stone dust would consume considerable number of man shifts, the so-called bulk stone-dusting system may be adopted. Experience with bulk stone-dusting in American mines has shown that considerable savings can be effected from it and that the total capital invested can be realized within a short time. In the bulk stone-dusting system as practised in the American mining industry, the stone dust is transferred from a surface, storage bin into large-capacity bulk supply cars underground through a lined borehole (Fig. 54) by means of an aerator feeder. The bulk cars are transported to different sections of the mine where the stone dust is transferred to stone-dusting machines, by screw-type conveyors. In a shift, two stone-dusting men can handle about 20 t of bulk stone dust including filling the bulk car at the borehole, transporting it to the section, filling the hopper of the dusting machine and stone-dusting.

The cost of stone-dusting depends on the cost of labour, the method of stone-

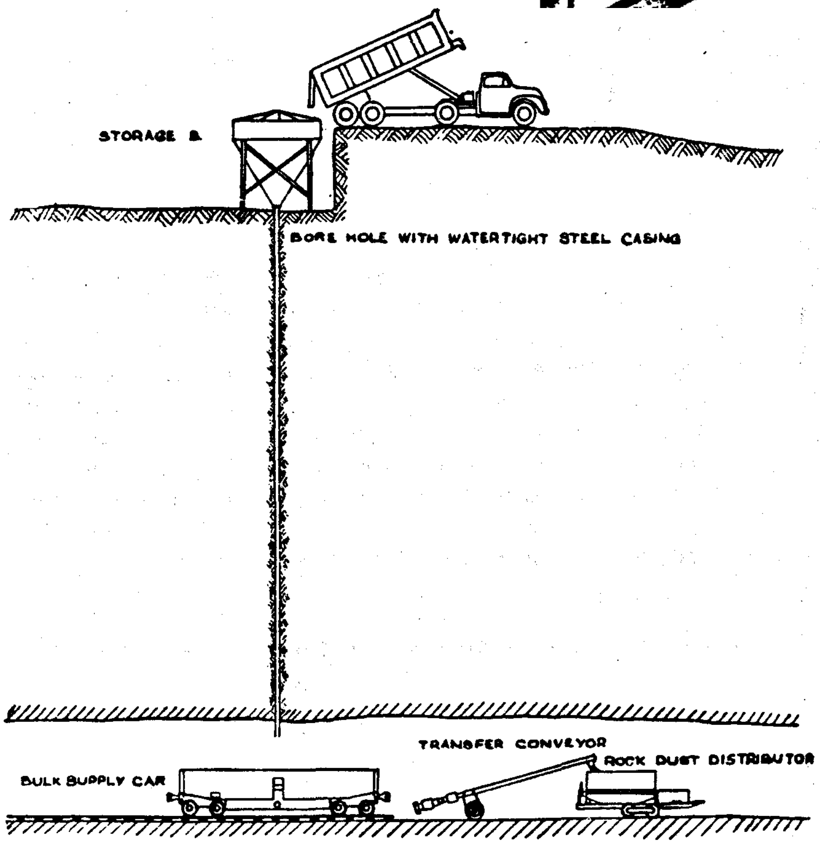


Fig. 54 M.S.A. Bulk Rockdusting System.

dusting adopted, and the system of mining by longwall or room-and-pillar.

To increase the adherence of the stone dust on the sides and roof of roadways which are dry and smooth or when stone-dusting is to be done during a working shift without creating undesirable dust clouds, wet stone-dusting has been tried in some coal mines in the U.S.A. Wet stone-dusting consists in applying wet stone dust in the form of .a premixed slurry fed from a guniting machine through a guniting nozzles or by mixing dry stone dust with water at the nozzle of a commercial stone-dusting machine (Fig. 55). It is limited to side and roof surfaces, the floor being dry stone-dusted manually. Experiments in the U.S. experimental coal mine [32, 33] on the effectiveness of wet stone-dusting in arresting the propagation of explosion have shown that

(a) mixture of 20 to 30 litres of water with about 45 kg dust gives good results from the standpoint of adherence ;

(b) Wet stone dust should be applied at a rate of not less than 0.92 kg of dust per square metre of surface area to yield a good covering of the side-roof surfaces;

(c) The rate of drying of the stone dust varies with the air velocity and relative humidity. With normal air (currents and relative humidities below 80%, the stone dust dries completely in 1 to 3 days and at humidities of 80 to 90%, it dries in about a week ;

(d) Wet stone-dusting is less effective than dry stone-dusting in arresting the propagation of an explosion.

2.2.10.3.2.3 Testing of Stone Dust before Use in Mines

Stone dust must be tested at the mine laboratory for fineness and dispersability.

Testing for Fineness

From the consignment arriving at the mine, a gross sample of approximately 2 kg is taken and reduced to 250 g by coning and quartering or by means of a sample divider. The representative sample is taken in an air-tight container to the mine laboratory where it is spread on a tray and allowed to air-dry for 24 hours. 100 g of the air-dried sample are then sieved using prescribed sieves and the amount of dust remaining on the sieves and in the receiver weighed to find the percentage fractions.

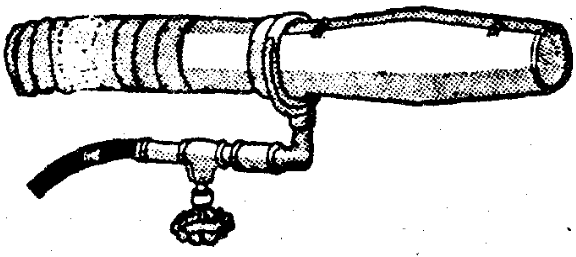


Fig. 55. Wet Nozzle.

Testing for Dispersability

The simple test which satisfies mining regulations consists in spreading the dust on the palm of a hand and seeing if a portion of it can be blown off by the mouth or by a suitable appliance.

For impregnated or water-proofed dusts which remain freely dispersible under wet mine conditions, the above test will give erroneous results as they are usually finer than untreated dusts and have stronger cohesive forces between particles so that when blown by the mouth the do not readily disperse but leave a portion on the palm. To test the dispersability of untreated and treated dusts fairly reliably, a method hi been developed in the Saar Coalfield, Germany {34] in which an accurate! weighed stone dust sample placed in a clean dry glass basin is blown 01 for a definite period by means of air flowing out of a capillary nozzle which is constantly moved without touching the glass basin. The stone dust deemed to be dispersible if the percentage of the dispersible fraction exceeds a definite value.

2.2.10.3.2.4 Mine Dust Sampling

The only certain means of determining the adequacy of stone-dusting is by sampling the mine dust at regular intervals depending on the intensity of coal dust production hi the mine and testing it for incombustible content. For this purpose, the mine should be divided into zones which should be distinctly demarcated underground and representative sample taken from each zone at such intervals of time as may be prescribed regulations. The length, number, and location of such zones should clearly shown on a plan called the Sampling Plan. The mine workings places in them from which it is not necessary to collect samples are main shafts, production faces, development headings for opening up of face loading and transfer points, and workings and places which are naturally wet or treated with dust-binding salts. The results of the analyses or te should be recorded in a special book (Dust Register) kept at the mine the purpose, which shall also show the place (location in the zones), date of last stone-dusting at the sampling place, and time of sampling.

It must be clearly understood that while sampling can indicate the section of a roadway is in a dangerous condition if the samples are be standard, it cannot give an assurance that samples with incombustible contents above the prescribed value reflect safe conditions. This is because the presence of coal-rich patches or coal-rich surface layers would not revealed by the present sampling techniques.

2.2.10.3.2.4.1 Equipment and Method of Sampling

The sampling equipment consists of:

1) A sampling scoop or dust pan having a width of 100 or 150 to collect the sample.

2) A standard sieve of prescribed mesh (BSS 60-mesh in the U.K. 10-mesh in the U.S.A.).

3) One or two pieces of oilcloth or rubberized cloth about 60 x cm on which to mix the representative sample, and to quart until there is just sufficient to sieve.

4) Sample containers 250 or 500 cm^3 or envelopes and labels can be pasted on them to carry the samples from the min the laboratory.

5) A pencil and book.

6) A carrying canvas sack or sectionalized carrier box.

The collection of a representative sample from a zone is usually by method of "strip sampling" by which the mine dust is collected fro succession of transverse strips as nearly as may be of equal width (100-150 mm) taken at such number of places or such distance from one and over such length of zone as may be prescribed by regulations. When collecting a sample, the sampler should walk against the ventilating current

At any sampling section, two kinds of samples are collected: the sample and the side-roof sample. The floor sample comprises dust collect to a depth of 25 mm on the floor from side to side provided that the material is found to that depth while the side-roof sample comprises collected to a depth of 6 mm as near as may be on the roof and side.

The surfaces of fixed structures in the roadway are considered to be part of roof and sides.

The floor and side-roof samples may be combined into a single sample and a single representative sample (250 to 500 g) obtained after mixing, quartering, and passing a portion through the prescribed sieve (peripheral or band sampling) or separate representative samples obtained from each of teem. Intensive sampling studies conducted by the U.S. Bureau of Mines 135] m an operating coal mine had revealed that band sampling can be] substituted for the more time-consuming and tedious floor and side-roof sampling without any sacrifice of safety. But one serious disadvantage of ban sampling is that in mines excess stone dust will be spread on the floor, with little or no stone dust on the sides and roof and vice versa. Collection of separate floor and side-roof samples is, therefore, the more reliable method of ascertaining the adequacy of stone-dusting.

The incombustible matter of total dust at a sampling place is given by

$$I_t = \frac{I_{sr}W_{sr} + I_tW_t}{W_{sr} + W_t}$$

where

I_{sr} is incombustible content of side-roof sample, per cent

I_t is incombustible content of floor sample, per cent

W_{sr} is weight of side-roof sample, kg per linear metre

W_t is weight of floor sample, kg per linear metre.

2.2.10.3.2.4.2 Analysis of Mine Dust Samples

The representative mine dust samples are analyzed for the incombustible matter content by approved methods of analysis. Chemical analysis m the laboratory is by far the most reliable of all the methods. Less accurate but simpler and more rapid are the calorimeter and volumeter methods of estimation with which the time and labour required for collecting and analyzing mine dust samples is considerably reduced. Incombustible dust analyzers for on-the-spot evaluation of the adequacy of stonedusting have been recently developed in the U.S.A. and are being evaluated.

2.2.10.3.2.4.2.1 Chemical Analysis

For routine dust analysis, chemical analysis consists of determination' 01 the moisture and ash contents.

*Moisture **Content** A* weighed quantity (1 g) of the representative sample should be dried at a temperature of between 105° and 110°C. The loss of weight represents the moisture.

% Moisture in sample = [(weight loss of moisture) / (Weight of dust sample)] X 100

Ash (Incinerated Residue) Content

In the 'High Temperature Incineration Method', the residue remaining after moisture determination should be heated to a temperature of 925° ± 25 °C in a muffle furnace for 1 to 2 hours until it no longer loses weight, and the weight of the incinerated residue determined.

% of Residue (Ash) = [(Weight of residue) / (Weight of original sample)] X 100

The sum of the weights of the moisture and incinerated residue should be reckoned as 'incombustible Matter'.

In the case of dust samples containing carbonates as happens when limestone dust is used for stone-dusting, the weight of carbon dioxide liberated during incineration should be reckoned as incombustible matter. The weight of carbon dioxide content of the sample can be determined by treating a weighed portion of the sample with dilute (10%) hydrochloric acid and finding the loss in weight or measuring the volume of carbon dioxide given off and calculating its weight.

$$\% \mathrm{CO_2} = \frac{\text{Weight loss of } \mathrm{CO_2}}{\text{Weight of original sample}} \times 100$$

If it is necessary for a sample to be air-dried before being sieved through a prescribed sieve, a correction must be applied to the incombustible matter determined for the loss of moisture during drying.

In the 'Low Temperature Incineration Method', the dust sample **is** incinerated at a temperature of not less than 500°C and not more than 530°C until it is constant in weight. This temperature is sufficient to complete the combustion of the organic matter in the sample but not high enough to decompose the carbonates.

2.2.10.3.2.4.2.2 Colorimetric Methods

There are two rapid practical methods:

1) Visual colour comparison method
2) Colour measurement method by reflectometer (Instrument sorting)

In the visual colour comparison method, the colour of a representative \ample is compared in the mine with that of standard dust mixtures prepared from actual mine dust samples and known to contain definite percentages of incombustible matter. To eliminate underground all sample that contain 80%- or more incombustible matter which would mean a considerable saving in effort, a single standard dust mixture containing 80% incombustible need only be used.

In the colour measurement method by reflectometer, the light-reflective' properties of the surfaces of mine dust samples are measured by means of photoelectric cells. The reflectometer must first be calibrated for different mines and seams by tests on standard dust mixtures for each mine and seam and plotting the relation between the inert content of the dusts as obtained by chemical analysis and reflectometer readings. From the calibration curves, the percentage of inert content in an actual mine dust sample corresponding to the reflectometer reading obtained can be read off. The reflectometer method can be used to sort dusts having inert content between 30 and 80%.

An ovious disadvantage of the colorimetric methods is that the colour of mine dust samples is affected by various contaminants, particle .size of coal dust, rank of coal, particle size of stone dust, moisture content, degree of mixing of coal and stone dusts, lighting conditions, etc.

2.2.10.3.2.4.2.3 Volumeter Method

This method is suitable for all dusts except those containing gypsum. It consists in measuring the specific volume of a weighed quantity of representative mine dust sample by the so called 'Volumeter'. The specific volume of a mine dust sample is given by the sum of the specific volumes of its constituents, namely, coal dust, stone dust and other dusts. If the specific volume of standard dust mixtures prepared from actual mine dust samples containing known percentages of incombustible matter be determined and a graph drawn there from, then the percentage of incombustible corresponding to the measured specific volume of a dust sample can be read off from the graph.

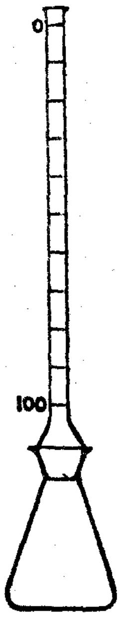


Fig. 56. Volumeter.

The volumeter consists of a 50-cm^3 flat-bottomed glass flask with a ground glass neck into which fits an open measuring stem about 20 cm long and 1.3 cm in diameter, graduated from zero at the top to 100 at the bottom (Fig. 56). The volume of the flask plus stem is 59.6 up to 100 graduation mark and 69.2 up to zero graduation mark.

To use the apparatus, first 25 cm^3 of methylated spirit are run into the flask and 25 g of the dust sample to be tested are then poured into it. After inserting the measuring stem into the vaselined neck of the flask, the flask is vigorously shaken by hand for 2 min to remove all air bubbles. The other 25 cm^3 of the spirit are then poured through the open end of the measuring stem and the reading of the level of the liquid in the stem noted. By reference to calibration graphs obtained for standard dust mixtures for different seams, the incombustible matter in a dust sample in any seam can be found out from the reading on the graduated stem.

To safeguard against discrepancy when using the volumeter method,

1 in every 50 samples should be check tested by chemical analysis. The accuracy that can be obtained with this method is ± 4% [36].

2.2.10.3.2.4.2.4 Combination of the Colorimetric and Volumeter Methods

When an increased through-put oi samples is to be achieved, a combination of colometric sorting and volumeter testing may be used. The samples are first sorted by the colorimetric method and those that are darker in colour than the standard dust are analysed by the volumeter method.

2 2.10.3.2.5 Efficacy of Stone-dusting

Extensive investigations carried in the German experimental mine [37] to test the efficacy of stone-dusting in suppression of coal-dust explosions had revealed that the legislative requirement of mine dust gives no guarantee that an explosion will not propagate through a stone-dusted roadway. The experiments had clearly brought to light the following important facts:

1) Stone dust does not form an intimate mixture with coal dust as was originally assumed.
2) Stone dust when overlain by a layer of coal dust does not prevent explosion propagation.
3) Explosions are not suppressed even when coal dust is covered with twice the quantity of stone dust by weight.
4) Stone dust is effective only when it overlays coal dust in a quantity which is 4 to 6 times the weight of coal dust.

From the foregoing, it is evident that stone-dusting as a practical measure does not offer adequate protection against propagation of coal-dust explosions unless coal dust and stone dust are thoroughly mixed and that it can only be considered as an additional or secondary measure of safety. Stone-dusting can be effective only in the mine workings where coal dust deposition is less.

2.2.10.3.3 Stone-Dust Barriers

Stone-dust barriers as a means of suppression of coal-dust explosions were first proposed by M. J. Taffanel and are today extensively used in the European mines. A stone-dust barrier is a device which will discharge by force of explosion (pressure wave) a mass of stone-dust in the form of a thick cloud into the path of oncoming explosion flame thereby smothering the flame.

2.2.10.3.3.1 Barrier Design

Experience had shown that of the various designs of barriers evolved and tested in Germany, Poland, and the U.S.A., the shelf barrier consisting of a number of dust-laden shelves independently supported transverse to and along the roadway in which it (the barrier) is installed, is the most practical design being less difficult to install and maintain.

Stone-dust barriers are installed in roadways leading from shafts or their pit bottoms, in all level and inclined roadways including gate roads and development headings, and near roadway junctions.

Two designs of shelves are commonly used in mines, the German (improved Dortmund type) Shelf and the Polish Shelf. The German shelf consists of several loose planks, maximum 60 cm long and 10 to 15 cm wide which are abutted along their length with the ends supported by cross pieces which rest upon two long transverse bars with their ends resting loosely on rigid shelf support (Fig. 57). The Polish Shelf is composed of several short planks 10 to 15 cm wide and 35 to 50 cm long laid alongside one another in the direction of the roadway (Fig. 58).

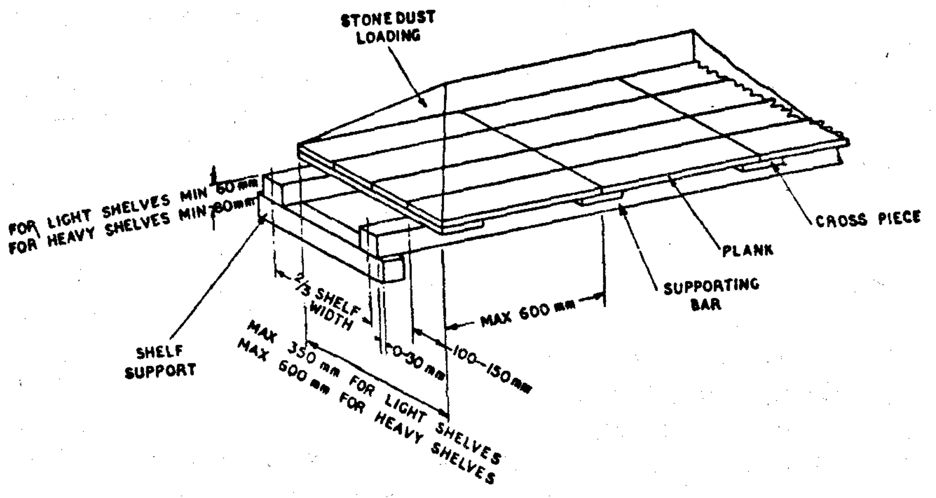


Fig. 57. German Shelf.

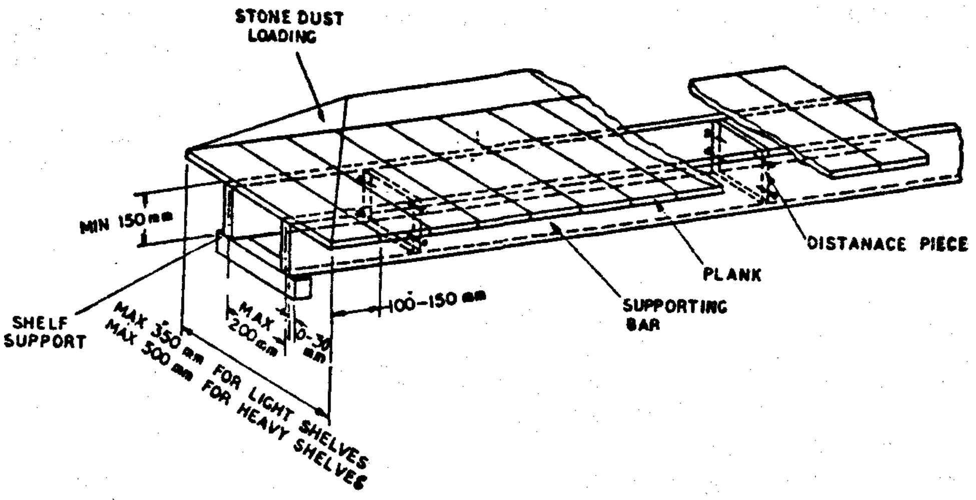


Fig. 58. Polish Shelf.

There are two types of German or Polish Shelf—the Lightly Loaded Shelf or simply the Light Shelf and the Heavily Loaded Shelf or Heavy Shelf.

In the German mines, both the German and Polish selves are officially approved for use in mines while in the U.K. only the Polish shelf is the officially approved one.

The specifications of the light (Type 1) and heavy (Type 2) German shelves as officially approved for use in the German mines in roadways up to 4 m high are given below.

	Light Shelves	Heavy Shelves
Width of shelves	max. 35	60 cm
Width of planks	about 10-15	10-15 cm
Length of planks	max.60	60 cm
Height of supporting bars	at least 6	8 cm
Distance between the supporting bars (centre to centre)	2/3 of shelf width	2/3 of shelf width
Weight of shelves/m length of shelf	max. 15	20 kg/m
Deflection of the supporting bars	max. 2% span width	max.2% span width
Dust loading on the shelf	at least 50	150 kg
	max. 100	300 kg

The specifications of the light and heavy Polish shelves as officially approved for use in the German mines in roadways up to 4m high ire given below.

	Light	Heavy Shelves
Width of shelves	max. 35	50 cm
Width of planks	about 10-15	10-15 cm
Length of planks	max. 35	50 cm
Height of supporting bars	Atleast 15	15 cm
Distance between supporting bars (centre to centre)	max. 20	20 cm
Weight of shelves/m length of shelf	max. 15	15 kg/m
Dust loading/m length of shelf	atleast 30	60 kg/m
	max. 35	70 kg/m

The following rules govern the erection of stone-dust barriers of both the types in the German mines:—

1) A stone-dust barrier must carry not less than 400 kg stone-dust per square metre average cross-section of the roadway.

2) At least a quarter of the total dust loading of any one barrier must be distributed on light shelves which must flank the heavy shelves of the barrier at either end. The heavy shelves must carry at least a quarter of the total dust loading.

3) The distance between the adjacent shelves of a barrier must be as given under:

German shelves: min. 1.50 m
max. 5.00 m

Polish shelves: light shelves between heavy shelves or between a heavy and a light shelf
min, 1.00m min. 1.25 m
max. 2.00 m max. 2.50 m

4) The bottom of the shelves should be at a height greater than half the roadway height but not exceed 2.60 m. The clearance between the ends of the shelves and the sides of the roadway should be at least 5 cm.

5) The brackets supporting the entire shelf must be rigidly fixed to the ground or roadway support. The shelf should never be suspended *from* chains or wire ropes which tend to swing.

6) The shelf supports at the brackets must be horizontal and have a smooth bearing surface; they should not project beyond the shelf supports by more than 3 cm.

7) The supporting bars must be rectangular in section.

8) The gaps between the planks must be covered with thin scantlings or strips having a maximum width equal to the width of the planks.

9) The clear space (vertical distance) between the top of the dust-loading and the inner edge of the roof bar or crown segment of the steel arch as the case may be at least *15* cm.

10) The dust-loading must be approximately symmetrical with respect to the centre of the roadway and must occupy at least two-third of the max. width of the roadway.

11) The dust-loading on shelf must not be covered.

12) In the vicinity of a barrier, ventilation ducting, overhung belt conveyors, pipes and other obstructions which seriously affect the effectiveness of the barrier, must not be present.

13) The barriers should not be installed at roadway junctions, at curves, or in widened portions.

In the U.K., the stone-dust barriers are of three types: the light, intermediate, and heavy barrier. Two types of Polish shelves are used. The light shelf whose width should not exceed 35 cm has a dust-loading of 29.8 kg/m shelf length while the heavy shelf whose width should not be less than 35 cm and not more than 50 cm is loaded to twice the value viz. 59.6 kg/m. The light barrier carries a total dust-loading of at least 107.4 kg/m^2 average roadway cross-section and comprises all shelves of the light type. The intermediate barrier carries a dust-loading of 195.3 kg/m^2 roadway cross-section and comprises not more than one-third of the shelves of the heavy type. The heavy barrier carries a dust-loading of at least 390.6 kg/m^2 roadway cross-section comprising not less than one-third of the shelves of the light type.

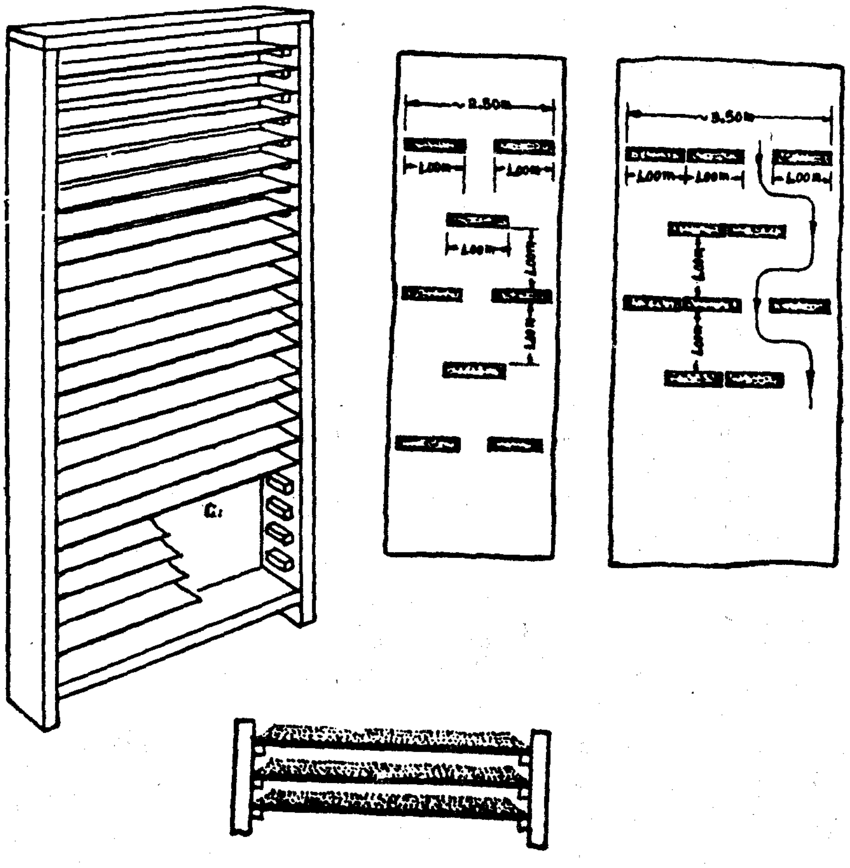


Fig. 59. Frame Barrier.

The distance between the adjacent shelves are:

light shelves	**between heavy shelves or between a heavy and a light shelf**
min. 0.91 m	min. 1.22 m
max. 2.10 m	max. 2.59 m

In India, the stone-dust barriers were officially adopted in the year 1963. The barrier types and design are similar to the British ones.

2.2.10.3.3.2 Barriers for Special Purposes

They are erected for special purposes such as for protection of men engaged in sealing off fire areas in mines. They art quick-acting and can be quickly erected. They carry 100 kg stone dust per square metre of roadway cross-section.

German 'Quick Barrier'

There are two types of quick barriers: the 'frame barrier' and the so called 'improvised barrier' (German 'Behelfs-Schnellsperre).

The frame barrier (Fig. 59) consists of several light shelves arranged in a light frame 2.10 m high and 1 m wide. The shelves are of plywood, 16 cm wide with a 5-cm deep layer of stone dust on each so that a gap of 5 cm between successive shelves is left for the ventilating current to pass through. The staggered placement of the frames allows room for men to travel through the barrier. The frames are either suspended from the roof or wedged tightly between the roof and floor. Fig. 59 shows the arrangement of the frames in narrow and wide roadways [38]. It takes about 40 min for 4 experienced men to erect these barriers.

The improvised barrier (Fig. 60) consists of several dust laden shelves arranged one above the other on shelf supports nailed to the side props of timber sets and centre props erected specially for the purpose on one or both sides of them depending on whether a staggered passage way is to be left or not. The shelves are longer and wider (width 30 cm) than those of the frame barrier.

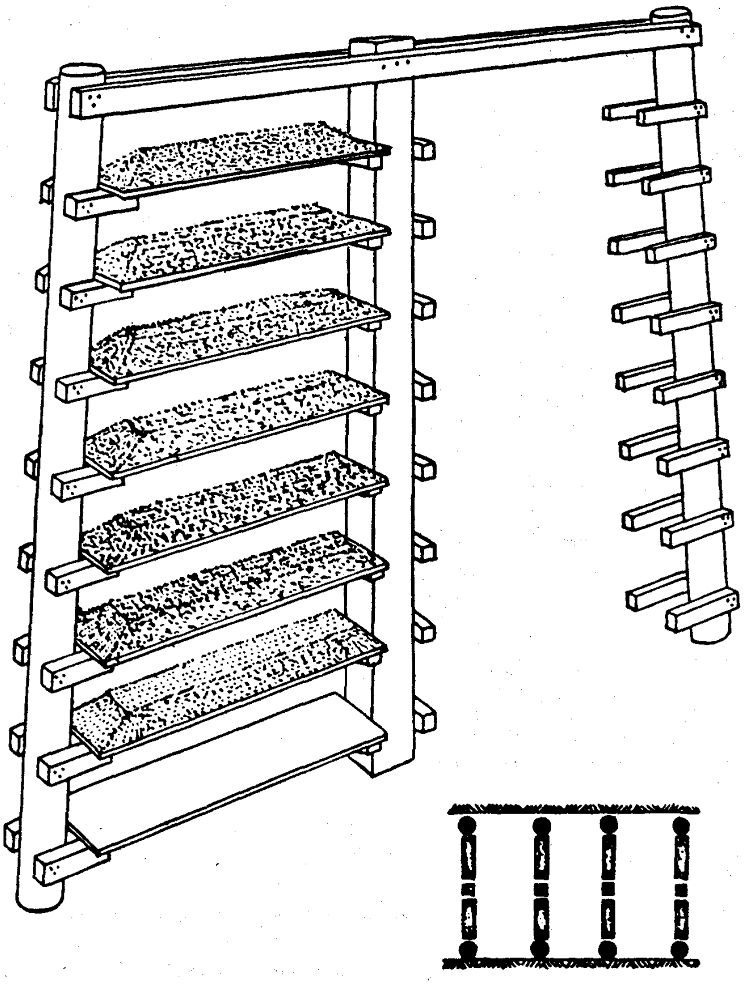


Fig. 60. Improvised Barrier.

It is recommended that the quick barriers be installed as far as practicable 30 to 40 m from the fire-seat and 100 m outbye the temporary stopping.

2.2.10.3.3.3 Efficacy of Stone-Dust Barriers

AH stone-dust barriers depend for their successful operation or the formation of a thick cloud of stone dust by the air blast of a coal-dust or firedamp explosion before being passed by the flame of the explosion. Experience with explosions in experimental and operating coal mines had shown that the force of explosion and the time interval between dust discharge and flame arrival determine the efficacy of a stone-dust barrier. The force of explosion and the time interval between arrivals of air blast (pressure wave) and flame at a barrier depend upon the design and location of the barrier, presence of flammable firedamp-air mixture, and the intensity of the explosion. A weak explosion may not throw the shelves off their supports. If the time interval between dust release and flame arrival is too long, a greater part of the dust falls to the floor but if it is too short, the dust does not get sufficiently dispersed. Experiments have shown that a time interval of 0.1 to 0.2 s *[25]* is sufficient enough to create a flame-quenching cloud.

In practice, stone-dust barriers may fail under any one of the following circumstances:

1) When the barrier itself lies in a flammable firedamp-air mixture or firedamp occurs as a roof layer.

2) When flame velocities are high (exceeding about 500 m/s) as when a dust explosion is initiated by a powerful firedamp explosion or is assisted by firedamp during its propagation.

3) When the barrier is located less than 40 to 60 m from a face or other potential point of ignition so that the flame velocities are low (less than 100 m/s).

4) When a powerful explosion is weakened by improper location or by stone-dusting.

2.2.10.3.4 Explosion-proof Stoppings

Unlike stone-dust barriers, explosion-proof stoppings localize firedamp or coal-dust explosions by isolating completely the explosion area from the rest of the mine. An explosion-proof stopping must, therefore, withstand, without being damaged, the full explosion pressure and also bring about extinction of the explosion flame by starving it of oxygen, it is mainly used for localizing explosions in parts of a mine in which there is less likelihood of wide spared propagation of an explosion such as development workings in coal and stone. In practice, explosion-proof stoppings are frequently erected in sealing of fire areas when there is danger of explosion due to firedamp or fire gases.

The stoppings may be constructed of brickwork, concrete, or timber. Wedge stoppings of brick, concrete block, and wood have been successfully used. Sometimes, heavy steel doors about 20 mm thick are used. They have the advantage that they can be closed quickly. They can also be used as 'blasting dams' in mine development work in gassy mines.

2.2.10.3.5 Salt Zones

Owing to the limited efficacy of generalized stone-dusting in preventing propagation of coal-dust explosions, experiments with salt zones were conducted in Germany for finding in them a much more effective substitute. Three fundamentally different processes were developed, namely, the Salt Crust Process, the calcium Chloride or Magnesium Chloride Paste Processes, and Calcium Chloride Powder Process all of which proved to be very effective in rendering coal dust indispersable so that it does not take part in an explosion.

2.2.10.3.5.1 Salt Crust Process

This process was first tried out at Beekerwerth Colliery in the Ruhr Coalfield. It consists in coating the sides, roof, and floor of a length of a roadway with a plastic mixture of rock salt (fine and coarse) and water by means of guniting equipment and wetting with sprays of water as dry salt crust is formed and a large quantity of coal dust is deposited on the crust. Under the influence of the ventilating current, the water evaporates and the salt crystallizes out through the coal dust forming with it a hard black crust. A great disadvantage of this process, however, is that it cannot be used where the relative humidity exceeds 80% or is below 55% when it becomes uneconomical.

2.2.10.3.5.2 Calcium Chloride/Magnesium Chloride Paste Process

This process depends for its action not upon the formation of crust by alternate processes of solution and crystallization but upon continued wetting of the coal dust by the hygroscopic calcium chloride or magnesium chloride paste. The hygroscopicity of the calcium chloride or magnesium chloride alone will not suffice to wet the dust unless a wetting agent (1 to 1.5%) is added to it. To improve adherence to rock surfaces, a gelatinous compound (magnesium hydroxide 2 to 3%) is added to the calcium chloride or magnesium chloride solution which then assumes pudding-like appearance. The percentage of calcium chloride or magnesium chloride in the paste depends on the underground climate conditions. It must be such that the paste maintains its pudding-like state for as long a time as practicable. At higher temperatures and relative humidities, the required concentration of the solution will be less than, at lower temperatures and relative humidities. Fig. 61 shows the variation of calcium chloride concentration with the relative humidity at 30°C [4]. The optimum concentration is best determined by trials. The quantity and kind of wetting agent depend on the quantity of coal dust to be neutralized by the paste in a definite time. It should be non-ionizing and also be cheaply available. Polyglycolethers are the best wetting agents. 1 kg paste binds about 5 kg dust and when applying for the first time about 5 kg paste per square metre surface area are required [39] so that with a roadway perimeter of 10 m (without floor) 50 kg of paste per metre length of roadway will be required.

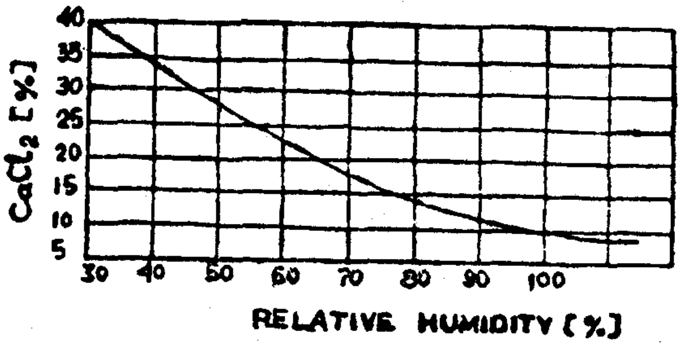


Fig. 61. Variations of $CaCl_2$ -Concentration with Relative Humidity at 30⁰ C.

A calcium chloride paste zone in a roadway is prepared by spraying the side-roof surfaces over a length of at least 80 m of the roadway with the paste and spreading flaked calcium chloride, a mixture of monohydrate and dehydrates of calcium chloride containing a wetting agent, evenly over the floor. The paste, if properly applied, remains effective for a period of a few weeks to six months depending on the amount of dust deposion, after which it should be sprayed afresh.

Experiments conducted in the German experimental coal mine under the several experimental conditions had shown that a coal-dust explosion does not propagate through the paste zone and that the explosion flame is extinguished within the first few metres of the zone [40].

Like a stone-dust barrier, a calcium chloride or magnesium chloride paste zone will fail to suppress an explosion if it is filled with a flammable firedamp mixture or has a layer of firedamp at the roof.

In Czechoslovakia, [4] greater reliance is placed on calcium chloride paste zones than on generalized stone-dusting or stone-dust barriers. In fact for the mines of the Kladno Coalfield, the mines inspectorate there has prescribed calcium chloride paste zones as the only safeguard against propagation of coal-dust explosions. But the paste used is a mixture of calcium chloride and finely-ground clay (Kaolin)'in the ratio of 1:1 by weight with a stabilizer (a sulphate or sulphate solution) added to it. The zones, at least 80 m long, are required to be formed at a distance of not less than 20 m and not greater than 300 m from a working place producing dangerous coal dust.

2.2.10.3.5.3 Calcium Chloride Powder Process

The calcium/magnesium chloride paste process suffers from a serious disadvantage that the paste containing 20 to 30% hygroscopic salt must either be transported in special containers to the place of use or pumped by high-pressure pumps where it is not possible to transport the containers. To overcome this difficulty, a mining company in the Ruhr Coalfield, Monopol Eergwerksgesellschaft mbH, Kamen, developed in 1965 in conjunction with Chemische Fabrik Kalk GmbH, Koln-Kalk, the Calcium Chloride Powder Process in which a fine-grained high-percentage calcium chloride powder (80 to 85% monohydrate $CaCl_2$, H_2O) containing a wetting agent (3%) is used in place of the paste. On account of its large surface area, the powder adheres to the roof and vertical surfaces. It takes up water vapour from the ventilating air becoming a solution and forms a paste with the deposited dust. The wetting agent acts through the paste.

1 kg powder takes up
1.3 lt water at 50% humidity
2.0 lt water at 70% humidity
4.6 lt water at 90% humidity

Depending on the relative humidity of the ventilating air, 1 kg of powder binds 3 to 7 kg of mine dust.

The powder is applied by machines which blow fluidized powder on to roadway surface through antistatic tubing. 2 men can apply powder over 160 to 300 m of a roadway in a shift.

1 tonne of powder (80% $CaCl_9$) costs at pithead four to five times the cost of 1 tonne of paste (20 to 30% $CaCl_2$).

The advantages of the powder process over the paste process art that the storage and transportation of powder in plastic sacks is simpler, roadway roof, sides and floor can be treated in one operation, and that it can be used under all humid conditions generally prevalent in the mines.

2.2.10.3.6 Water Barriers

In recent years, interest has revived in the use of water barriers as alternative to stone-dust barriers for the suppression of firedamp and coal-dust explosions in mines. Water has the following advantages over stone dust:

(a) its heat capacity is about five times that of dust;
(b) its efficacy is affected by underground climate conditions ;
(c) it is available in all mine main roadways.

A water barrier consists of a number of waiter-filled troughs of suitable material supported on horizontal shelves as in the case of a stone-dust barrier. The troughs shatter or burst under the action of the shock wave of an explosion distributing their contents in all directions in the path of the explosion flame.

Water barriers offer advantages over stone-dust barriers in cheapness and ease of installation and maintenance. Extensive tests on the performance of water barriers carried out at the Tremonia experimental mine in the Federal Republic of Germany showed that in quenching explosion flames, the water barriers were roughly equivalent to stone-dust barriers and that 200 1 of water per square meter of roadway cross-section would be necessary which would have at least the same effect as 400 kg stone dust per square meter on Dortmund shelves [41]. Besides the magnitude of the dynamic pressure, the shattering of the water trough is influenced by the kind of trough material, trough shape, method of installation, and trough covering. Wood and sheet steel are not suitable trough materials. Troughs made from special kinds of hard PVC or Styropor have been found to be most suitable materials as they are easily shattered at low pressures giving good water distribution. The troughs must be designed so that they maintain their shape with little sacrifice of their fragility.

The method of installation of the troughs in roadway cross-section exercises a great influence on the shattering of the troughs; troughs placed with their longer axis at right angles to the roadway axis offer greater" frontal area to the dynamic pressure than when they are placed parallel to the axis of the roadway.

Contrary to expectations, troughs supported in the roadway cross-section with their edges resting on transverse supporting frame have been found to shatter more easily than troughs supported on transverse bars. This is, because, the former are subjected to full dynamic pressure and cannot be displaced as happens with the latter. Also, the use of loose lids to prevent evaporation of water does not affect in any way the distribution of water in the direction of roof as the lid lifts itself off the trough.

Water barriers are at present widely used in German coal mines. Their design and installation are laid down in regulations. Depending on the method of support, two types of water barriers have been approved for use in German mines in roadways less than 4.0 m in height—Type 1 and

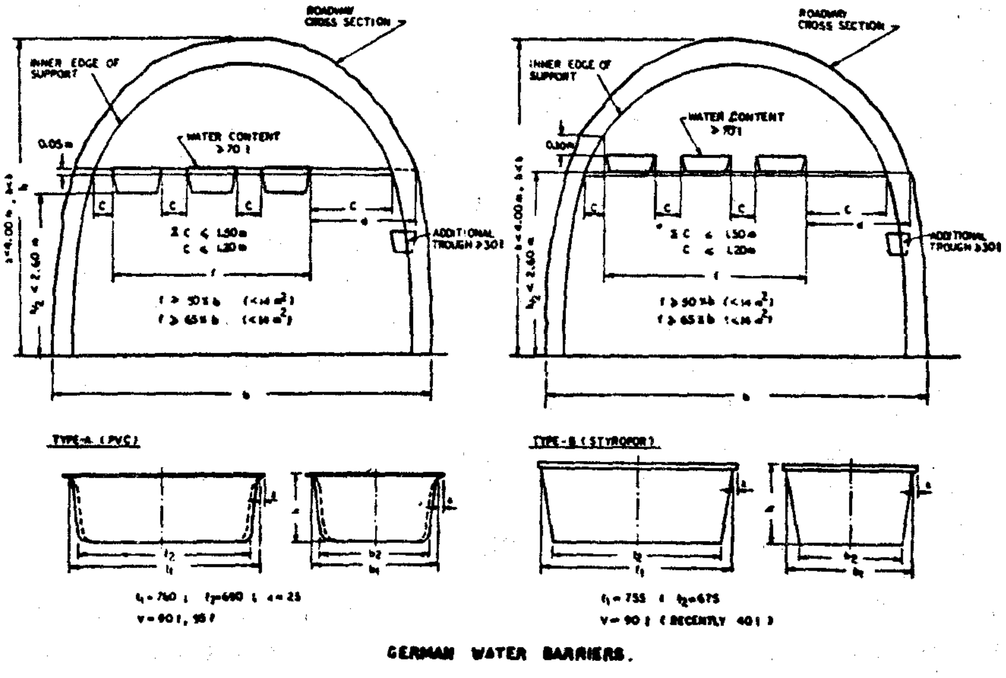


Fig. 62. Water Trough Barrier.

Type 2. In Type 1 barriers, the troughs are supported with their edges resting on transverse supporting frames while in Type 2 barriers, the troughs are placed over transverse bars. Fig. 62 illustrates the prescribed method of installation of water troughs carried by a shelf in roadway cross-section as well as two types of approved trough constructions.

The following rules govern the erection of water barriers in German mines:

i) The water barrier must contain at all times at least 200 litres water per square metre roadway cross-section or at least 5 1 per m^3 roadway volume and must be at least 20 m long.

ii) The distance between two adjacent shelve must be at least 1.20 m.

iii) The distance between edges of adjacent troughs carried by a shelf must not be greater than 1.20 m. When the distance between rib-side troughs and the rib or the inner edge of the roadway support is greater than 1 m. an additional trough containing at least 30 1 must be installed at the rib.

iv) The troughs must carry least 70 lt water. When there are two or more troughs on a shelf, each trough must contain not less than 30' 1 water.

v) The bottom of the troughs must be at a height of at least half the height of the roadway but not exceed 2.60 m. Where the top edge of the trough is higher than 1.80 m, the trough walls must be designed so that the water level can be recognized against marked graduations or a float provided in each trough.

iv) At all places where the barriers are installed, water from a water pipe must be available. Water hoses must be provided,

vii) The distance between barriers must not be greater than 200 m in gate roads and not greater than 400 m in main roads,

viii) A water barrier must be sited at least 100 m from a stone-dust barrier.

Large-scale investigations are at present being carried out in Germany on the effectiveness of the so called 'distributed' water barriers in which, instead of concentrating large quantities of water on shelves close together, the shelves are "distributed" as much as 10 to 30 m apart so that the length of the roadway covered is several hundred metres. The results so far obtained have been very encouraging and the distributed barriers have been found to suppress from weak to powerful explosions with static pressures up to about 6 bar, dynamic pressures up to 1.6 bar and *flame* velocities up to 500 m/s.

With distributed barriers, the quantity of extinguishing water is expressed me in litre or kilogramme per m^3 roadway volume. The quantity of water required has been found from trials in the experimental mine to be 0.5 lt to 1 lt/m^3, and the number of troughs required is no more than with the concentrated barriers which must be erected at distances of 200 m.

Distributed barriers seem to promise greater safety than the concentrated barriers. A coal-dust explosion in the initial stage may not develop adequate pressure to shatter a concentrated barrier and the explosion flame may pass trough it without being extinguished. There is a possibility that the explosion flame as it passed through 200 m of the roadway before it meets the next barrier, may develop into strong explosion and under circumstances into a very powerful explosion which the second barrier may not be able to suppress. The development of the explosion into a very powerful one in a few hundred metres long roadway with a distributed barrier is not possible. Even if the first or two shelves do not extinguish the flame, the following shelves will certainly suppress the flame. It will not be far when the distributed water barriers will replace the concentrated ones which are being installed to-day.

2.2.10.3.7 Triggered Barriers

Stone-dust and water barriers suffer from the disadvantage that they descend for their action on the dynamic pressure of the explosion. To make their operation independent of pressure, work on the so-called "triggered barriers" was started in Germany around 1966 in which a sensor or detector sensitive to temperature changes, or ultraviolet or infrared radiation emitted from explosion flame detects a developing explosion and sends signal to a disperser which disperse an extinguishing agent at right time in the path of the explosion. The initial experiments on automatic explosion barriers were conducted in large diameter pipes in which gas explosions were successfully suppressed by use of dry extinguishing powders as well as water. This stimulated further work not only in Germany but also in other countries especially of Western Europe in developing suitable triggered barriers for suppression of firedamp and coal dust explosions in mines. At present, the Experimental Stations in Germany, Belgium, France, and the U.K. are closely collaborating with each other in exchange of information and experiences on the design of suitable sensors and triggering mechanisms so as to avoid any duplication of effort and achieve success at the earliest possible time.

A suitable sensor must be sufficiently sensitive to react to temperature changes or to radiation from flame of any size of explosion. On the other hand, it must be selective so that it would not react to extraneous effects and influences such as those due to mechanical shocks, cable faults, stray electric currents, electro-magnetic interference, cosmic rays, air shocks produced by the normal use of explosives, mine lighting, heat from flame lamps or other sources. Its performance should not be impaired by dust, oil or water. The ultraviolet and thermocouple sensors have their own advantages and disadvantages. By suitable design some of the disadvantages can be overcome. Trials at SMRE, Buxton on UV-sensors have shown that UV-sensors are unreliable in operation with coal-dust explosions in which unburnt cloud of coal dust between the flame and the sensor may attenuate the UV-radiation to an insignificant level.

Two kinds of dust dispersion systems are being experimented upon. In one system, stone dust or $NaHCO_3$ held in a polythene bag or polythene-covered trough is dispersed by a detonator fired by a length of detonating fuse coming from an amplifier, while in the other, a detonator bursts the sealing disc or diaphragm of a rapid-release value of an inverted high-pressure steel cylinder containing the suppressant dust or water and nitrogen under a pressure of 30, 60 or 120 atg. A battery of extinguishing cylinders may be required to disperse the necessary amount of the suppressant in the path of the explosion.

Experiments are still in progress to overcome some of the handicaps the triggered barriers suffer from. Reliability and capital cost will be decisive for their application in mines.