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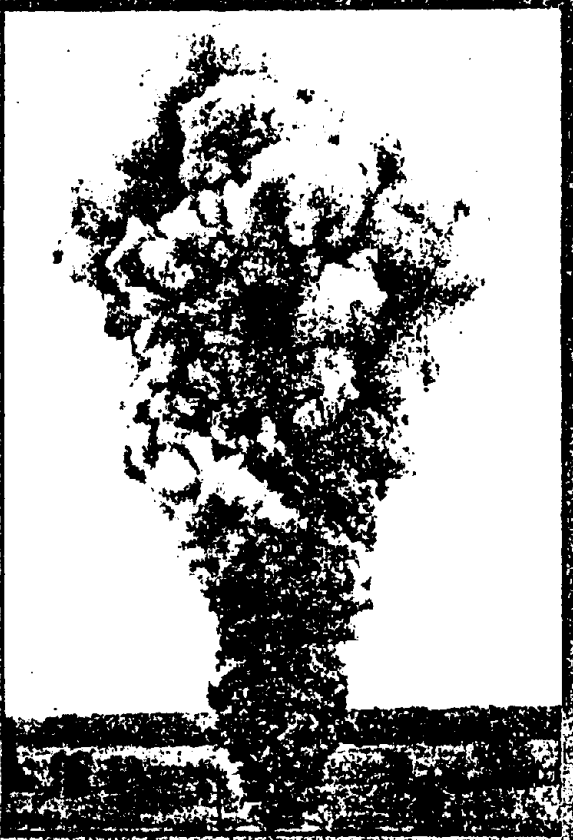
Wacław Cybulski



Coal dust explosions and their suppression

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Wacław Cybulski

Coal Dust Explosions and Their Suppression

(Wybuchy pyłu węglowego i ich zwalczanie)

TRANSLATED FROM POLISH

Published for the Bureau of Mines, U.S. Department of the Interior and the National Science Foundation, Washington, D.C., by the Foreign Scientific Publications Department of the National Center for Scientific, Technical and Economic Information
Warsaw, Poland 1975

Translation of the book "Wybuchy pyłu węglowego i ich zwalczanie"
published by Śląsk, 1973, 451 pp.

Translated by
Ziemisław Zienkiewicz

Available from the U.S. Department of Commerce,
National Technical Information Service, Springfield, Virginia 22161

I dedicate this work to the memory of the miners who lost their lives in explosion disasters in mines

This is the first book — not only in the Polish but also in the world literature — in which the entire up-to-date knowledge is contained about coal dust explosions and methods of suppressing them.

As far as the space permitted the basic conditions are also discussed here under which explosions of firedamp and coal dust can be initiated. The book contains the results of many years of investigations conducted in the Experimental Mine Barbara, reports of which were published in Polish and foreign periodicals. In the preparation of this book the author made use of the published works of the most eminent foreign authorities on the subject, particularly he had utilized papers read at international conferences of the safety in mines research institutes.

The book is intended for the use of workers of scientific research institutes and for students of mining academies.

PREFACE
THE PROBLEM OF COAL DUST EXPLOSIONS

Explosions of gases and of coal dust are the basic hazards in coal mining. Explosions in mines were and — unfortunately — continue to be the cause of numerous disasters in mines. Though, according to statistics, the frequency of explosions of firedamp, flammable fire gases and coal dust is relatively low — yet the combating of these hazards is still looked upon as a very important task since they have been the cause of the greatest disasters resulting in a tremendous number of fatalities.

Works on the means of combating the hazard of explosions in mines are being conducted — since over half a century ago — in many states, in scientific institutes organized especially for this purpose. The results of investigations carried out in these institutes are being gradually introduced into the mining practice with the effect that the number of disasters in mines has been considerably reduced.

In Poland in the *Experimental Mine Barbara*, otherwise called the Safety of Mines Institute, scientific research works on a large scale are being carried out since the year 1925 on the means of combating the danger of explosions of coal dust, firedamp and flammable fire gases. Whenever further in this book reference will be made to the Safety of Mines Institute it will be called by *EM Barbara* (in short for the *Experimental Mine Barbara*).

In spite of the up-to-date achievements of science all over the world explosions in mines still present a great potential danger. This assertion is confirmed by the series of disasters which occurred in coal mines of many countries in the years 1965–1970 (in France, Yugoslavia, Japan, Great Britain, the Federal Republic of Germany, the Hungarian People's Republic and the USSR).

The mechanization of the processes of winning and transportation of coal increases the amount of coal dust in mine workings. The exploitation of seams from deeper levels and a more rapid advancement of mine faces cause the emission of increased amount of firedamp into mine workings. As the result of this the potential danger of explosions in coal mines increases.

There is a rich scientific literature presenting the results of investigations on explosions in mines carried out by scientific-research institutes.

However, as the world practice shows, it is chiefly scientific workers who get acquainted with their respective problems through the study of original works. Yet, the most effective and the quickest acquisition of the basic information on a given problem can be achieved through books in which everything pertaining to that particular problem will be presented in a sufficiently precise but, at the same time, a concise manner. Such books can also serve as an everyday aid in the elucidation of doubtful questions with which one is confronted in the course of operating mines. Such handbooks make it possible to reduce the extent of regulations which, in the absence of appropriate books, become very comprehensive and overloaded with detail.

Neither in the Polish, nor in the world literature dealing with coal dust and firedamp explosions, the author of this book could find a manual on a university level in which the entirety of these problems were treated.

In order to avoid any misunderstandings it should be stressed that in many countries, and among them also in Poland, there have been published books, booklets and reports prepared by commissions appointed to study the danger of coal dust explosions. The level of these publications does vary but many of them are quite valuable. They are not, nevertheless, of the type fulfilling the requirements one would set for a manual on a university level.

From among Polish publications of this kind, works should be mentioned the titles of which are given under the numbers [71] and [105] and from foreign publications under the numbers [15], [72] and [169] in the references at the end of the book.

It is possible that there are other valuable up-to-date publications containing something like a summary of information in the field of coal dust explosions. However, the author of this book could include in the list of literature of the subject only such books which were sent to him, at his request, by proper scientific-research institutes.

According to the author's personal experience of many years in a considerable number of mine disasters, the fundamental cause has been the lack of appropriate knowledge of matters connected with the problems of explosions among the superintendents of mines. If this knowledge were sufficient almost certainly the negligence in the fulfilment of regulation requirements would have been less frequent and many a disaster could have been avoided. In the problem of coal dust hazards conditions are usually so manifold, and there are so many factors affecting the degree of the danger of explosion that the knowledge, particularly of the fundamental facts about them by the people who supervise mining operations, is of paramount importance to the effective and economical suppression of disasters.

Pioneers of investigations in the field of coal dust explosions.

To write a book including the entirety of the actual knowledge in the field of coal dust explosions would have been, undoubtedly, a useful undertaking but its usefulness would be restricted to a limited circle of mine employees and, moreover, it would not be an easy task to find in such a voluminous work the information one might urgently need at a particular time. On the other hand if the book were to include only the information necessary for a normal operation of mines the book would not fulfil the purpose for which it is intended. Thus this book represents a compromise, but — at any rate — it treats the problem of coal dust explosions on a university level.

The rapid scientific and technical progress we are witnessing now makes books on technical subjects to become obsolescent in a relatively short time. This discourages many scientific workers from writing books. The long time needed to publish a book makes the situation even much worse and brings harm to the course of progress. Particularly harmful is the situation described above in the field of the safety in mines. One is inclined to believe that only on account of the factors stated here the most renowned investigators of coal dust explosions — to name only such experts as Taffanel, Chernitsyn, Wheeler, Tideswell, Rice and Beyling — have never written books on this problem.

There is always a certain time interval between the achievements of science in particular fields and the practical utilization of these achievements. One of the aims of the present book is to shorten this interval.

In considering the problems of coal dust explosions in this book one had to keep in mind that there is no corresponding work on the hazard of firedamp. The author of the present book, therefore, dealt with the latter problem at least to the extent to which it connects directly with the hazard of coal dust explosions.

Coal dust explosions are responsible for such great disasters in mines that, actually, the tragic record of the largest number of fatalities in a single disaster belongs to disasters caused by these explosions. Disasters of this type occur since the time when deep collieries — in which firedamp was present — began to be exploited or in which the use of mining gunpowder was introduced.

During the 18th and through a large part of the 19th century all explosions in mines were attributed to mining gas ultimately identified as methane thanks to the progress of chemistry.

Suspicions that coal dust also has its part in mine explosions date back to the year 1803 when (after an explosion in the British mine at *Wallsend*) J. Buddle reported that during the explosion sparks of the inflamed coal dust were observed.

After explosions which occurred in the British mines: *Jarrow* (in the

year 1830), *Wallsend* (1835), *Springwell* (1837) and *Thomsley* (1834) coked coal dust was found which indicated its participation in the explosions.

Faraday was the first to recognize the danger of coal dust explosions. This great scientist, after the explosion in the *Haswell* mine in the year 1844, expressed his opinion that coal dust played an active and substantial part in it; however, not much attention has been paid actually to this opinion by the mining industry. Even scientists of such eminence as Mallard and Le Chatelier expressed their conviction that no explosion can be ascribed to coal dust (1882).

Gradually, however, it had been admitted that coal dust can have a share in methane explosions. The presence of methane, however, was considered to be indispensable for an explosion to take place.

Great Britain has to be credited with the definite determination of the hazard created by coal dust. It was there that a commission was appointed in 1879 to investigate the problem of explosions in mines. In the commission's report of 1894 it has been stated that coal dust can explode by itself without the participation of methane. This was established experimentally for the first time by H. Hall in the dip-heading mine *Big Lady* where his experiments were carried out.

Notwithstanding the establishment of this fact the industry delayed in taking this great problem seriously into consideration. The crucial occurrence which started investigations on the explosions of coal dust and the ways of suppressing them was the disastrous coal dust explosion in the *Courriers* mine on March 10, 1906. There were 1099 fatalities caused by it. The explosion affected the entire southern part of the mine (the range of the disaster covered an area about 5 km long and about 1.5 km wide) in which about 1800 miners were working at the time. Most probably the explosion was initiated by shotfiring. Firedamp could not have had any part in the explosion since at the time no methane was present in the *Courriers* mine. After this explosion there was no doubt left concerning the explosibility of coal dust as such. This terrific disaster shocked the opinion of the whole civilized world the more so, since the rescue activities after the explosion were not less dramatic than the explosion itself. The action of rescuing the miners was not properly organized. On the second day after the explosion the persons, responsible for rescue activities, decided that no man could possibly remain alive down there where the explosion occurred.

As the result of the explosion fire ensued. Therefore changes were made in the direction of ventilation air currents for the purpose of facilitating the extinguishing of the fire. No attention had been given to the possibility of some miners being still alive. Twenty days after the explo-

sion the public opinion was deeply shocked again by the news that 13 men worked their way out of the explosion area. They survived by staying in blind workings to which no carbon monoxide penetrated. To feed they used oats intended as fodder for horses and whatever remains of food they found on their dead companions. Five days later, that is, 25 days after the explosion, still another man, named Berthon, worked himself out of the mine — a fact worth mentioning because of the extraordinary fortitude displayed by him.

In the Polish mining history a miner, Alojzy Piontek, secured a place for himself; from a disaster in the *Rokitnica* mine he was saved after 158 hours endured under extremely hard conditions with coal piled up over him, with no water and no food.

The essential cause of the disaster in the *Courriers* mine had been the absence of any means of suppressing the danger of coal dust explosions. It was this terrible disaster, however, that prompted many countries to begin investigations on the problem of coal dust explosions. The most comprehensive, really pioneer, investigations were carried out in France by J. Taffanel in an experimental gallery on the surface at *Liévin*. The results of Taffanel's investigations [166] were first published in the year 1907. It started a series of papers published in the *Annales des Mines* in the years 1910, 1912 and up to 1921 [167]. Investigations conducted by Taffanel comprised not only a thorough study of parameters of coal dust explosions but also a study of the means of suppressing these explosions: the dusting with stone dust, spraying with water, stone dust and water barriers. Great contributions made by Taffanel as a pioneer in the field of the investigation of the problems of coal dust explosions are recognized by the mining circles everywhere. Among the pioneers in this field a Pole, J. Czapliński, should also be counted. Together with Jicinsky he carried out very valuable investigations in an experimental gallery at *Rosice* [19].

In Russia, the first works in this line of study were carried out by Chernitsyn at *Makeevka* before the World War I. The name of this investigator deserves particular remembrance since he died a heroic death during rescue activities in a Donets Basin colliery.

Photographs of all pioneer investigators of coal dust explosibility are given in this chapter.

The first scientific-research institutes, commonly referred to before as experimental stations, were — in the mining industry — establishments whose aim was to suppress coal dust and firedamp explosions.

Nowadays in every country having a developed mining industry there is a scientific research establishment investigating the methane and dust hazards. In many countries such establishments are in fact institutes with very large programs of inquiries concerning problems connected with the safety of work in mines. The list of these institutes is given below:

Country	Name of the scientific research institution	Located at:
Australia	The University of Sydney, Department of Mining Engineering;	Sydney N.S.W.
Belgium	Institut National des Industries;	Liège
	Institut National des Industries;	Paturages
Bulgaria	The Scientific Research and Design Institute for Mining and the Enrichment of Ores;	Sofia
Czechoslovakia	The Scientific Coal Research Institute;	Ostrava Radvanice
France	Centre d'Études et Recherches des Charbonnages de France;	Paris 7e
	Laboratoire du Centre d'Études et Recherches de Charbonnages de France;	Verneuil-Halatte
Holland	The State Mines of Limburg, Central Research Station;	Hoensbroek-Treebeek
India	Central Mining Research Station;	Dhanbad, Bihar
Japan	Resources Research Institute;	Kawaguchi-Saitama
	Experimental Mine;	Fukuoka
Yugoslavia	The Ore Institute;	Beograd-Zemun
German Democratic Republic	Institut für Grubensicherheit;	Leipzig
	Bergakademie;	Freiberg
Federal Republic of Germany	Steinkohlenbergbauverein;	Essen
	Versuchsgrube Tremonia;	Dortmund
Rumania	Ministry of the Mining Industry, Scientific Research Institute of Geology;	Petrosani
	Research Station for the Safety of Mines;	
USA	United States Department of the Interior, Bureau of Mines;	Washington
	Experimental Mine;	Bruceton
	Bureau of Mines;	Pittsburgh
Hungary	Banyászati Kutató Intézet;	Budapest
	Pérsi Szenbanyaszati Troszt;	Pecs
	Tatabányai Szenbanyaszati Troszt;	Tatabánya
Great Britain	National Coal Board, Mining Research Establishment;	Isleworth
	Ministry of Technology, Safety in Mines Research Establishment, Central Laboratories;	Sheffield
	Ministry of Technology, Safety in Mines Research Establishment, Central Laboratories;	Buxton

USSR	The A. A. Skochinski Mining Institute;	Moskva
	The State "Makeevka" Institute of Scientific Research on the Safety of Work in the Mining Industry MakNII;	Makeevka
	The Eastern Institute of Scientific Research on the Safety of Work in the Mining Industry, WostNII.	Kemerovo

It should be said that the scope of activities of these establishments is very much diversified and so is their organization.

There is a collaboration between these establishments, a fact of great importance for the progress of investigations on the problems of safety in mines. This collaboration was initiated in the year 1931 by an Englishman named Wheeler. At first it included only several West-European states, Poland and the USA. Since the international conference, organized in the year 1961 in Warsaw, this collaboration extended to include practically all the above named institutes and establishments. It consists in the organization, at two-year intervals by every interested country in turn, of international conferences at which the latest works presented by scientific workers are discussed. This collaboration gives very good results. It is not possible for a single country, no matter how rich, to carry out investigations concerning all problems.

For this reason it is absolutely necessary — in the interest of the progress in combating the hazard of explosions — that the latest scientific works and the most actual problems in this field, as they emerge in different countries, should be discussed.

The collaboration between the establishments mentioned above is, naturally, not restricted to the international conferences; this would be hardly sufficient. The establishments in question not only exchange their latest publications but also inform each other about the works upon which they are actually engaged. Groups of these establishments work jointly on larger problems and plan accordingly the themes of their particular researches. The establishments exchange their scientific workers for longer practice periods with excellent results. In the interest of the safety of work in mines it is necessary to take good care of the further development of the worldwide collaboration in this field.

1. INTRODUCTION TO THE PROBLEM OF COAL DUST EXPLOSIONS

1.1. STATISTICS OF EXPLOSIONS IN MINES

1.1.1. General information

There is no need to argue that precise statistical data concerning explosions in mines is very helpful in combating these disasters. Of course, mere statistical schedules are not sufficient; it is necessary to have accurate data about the causes of explosions and their course.

Unfortunately no world statistics are available though they would be of great value. In the present author's opinion such statistics ought to be collected by the International Labor Bureau at Geneva.

In the circumstances the present author had the access only to Polish statistics and to statistics of certain other countries. He tried to collect data from all countries but his collection is not complete in any way.

1.1.2. Statistics of explosions in Polish mines

The statistical data about explosions in Poland is divided into that relating to the prewar, and that which concerns the postwar period.

The very strong development of the coal industry after the war makes it actually impossible to compare the two periods. Nevertheless the arrangement of statistical data in Table 1.1 is very useful: it presents all explosions between the years 1922 and 1970, inclusive, in which there were casualties among workers.

Apart from the number of casualties the causes of explosions (the initiators), the kind of explosion, the system of ventilation and the range of the flame are shown in the table only in the cases, of course, when it was established through results of researches carried out in the *EM Barbara*.

It must be explained that Table 1.1 contains only the disasters which occurred in mines under Polish administration. Therefore this table does not contain the most serious disaster which took place in the year 1923 in

Table 1.1

A List of All Explosions Registered in Polish Mines in the Years 1922–1970 in which Casualties Had Been Recorded (the War Period Excluded)

No.	Date of accident	Mine, seam methane hazard class of dustiness	Ventilation	Kind of explosion and place of its initiation	Initiator	Way of the flame	Number of casualties by categories			
							I	II	III	IV
1	2	3	4	5	6	7	8	9	10	11
1	June 1922	*Milowice*, 510 nonmethane, class B	main	coal dust explosion in a coal getting gallery	rock explosive (*Miedziankit*)		7			
2	1923	*Reden*		explosion of flammable fire gases and of water vapor	fire		39	10		
3	August 16, 1929	*Wanda-Lech*, 501 little methane, class B	main	coal dust explosion at a short-wall face	permitted explosive (*Metanit*)	400	16			
4	September 22, 1934	*Walenty-Wawel* fiery heap		ignition of a coal dust cloud over a fiery heap	a fiery heap		13		27	
5	January 1936	*Dorota*, F (Podveden 36) nonmethane, class B	auxiliary	coal dust explosion in an inclined plane	rock explosive		2			
6	June 10, 1945	*Brzeszcze*, XXV category III, class B	main	methane and coal dust explosion in a belt-conveyor road with the auxiliary ventilator switched off	permitted explosive		9			
7	January 9, 1946	*Anna*, 705 and 713 methane	main	methane explosion in a cross-cut	electricity				2	
8	November 6, 1947	*Marcel*, 712 J category II, class B	auxiliary	methane and coal dust explosion in a transportation roadway	tobacco		5			
9	January 28, 1949	*Jankowice*, 504 (H) strongly methane, not classified	auxiliary	ignition of methane in the air heading	exploder			1	1	

Table 1.1 (continued)

1	3	3	4	5	6	7	8	9	10	11
10	1949	*Bobrek*, 412	auxiliary	ignition of methane (twice at 10 min interval) in the rise gallery in the 412 seam	open light			2		
11	June 20, 1949	*Bochnia*, level 387 strongly methane	main	formation of a methane outburst in the *Coballini* crosscut, and explosion of the methane-air mixture	open light		4			
12	May 4, 1950	*Jankowice*, 507 category III, class B	main	methane and coal dust explosion in a gallery	exploder	2000	29			
13	September 13, 1950	*Wanda-Lech*, 504 methane, class B	main	methane and coal dust explosion (in the rise gallery) at a crossing of galleries.	electricity	580	3	4		
14	February 14, 1951	*Wieczorek*, 620 category II, class B	auxiliary	methane and coal dust explosion in the rise gallery	tobacco	150	3			
15	December 24, 1951	*Myslowice*, 407 category II, class B	auxiliary	methane and coal dust explosion in the rise gallery	tobacco	170	7	4	5	10
16	August 7, 1952	*Pstrowski*, 509 nonmethane, class B	main	flammable-fire-gases-and-coal-dust explosion in a pillar crosscut	open light	100	9	11		
17	August 12, 1952	*Wanda-Lech*, 418 methane, class B	auxiliary	methane and coal dust explosion in a gassy gallery	electricity	500	2			
18	March 4, 1953	*Boleslaw Chrobry*, 30 category II, class B	main	methane and coal dust explosion in a sidewall	permitted explosive (*Barbaryt*)		5		8	10

Table 1.1 (continued)

1	2	3	4	5	6	7	8	9	10	11
19	September 1, 1955	*Wieczorek*, 620 category II, class B	main	ignition of methane in the air heading	permitted explosive (*Metanit*)			6	4	
20	July 18, 1956	*Boże Dary*, 318 class B	main	flammable-fire-gases-and-coal-dust explosion	open light	700	24	12	67	
21	November 2, 1956	*Łagiewniki* nonmethane, class B	main	coal dust explosion in a descending rock gallery	electricity	440	8		5	
22	January 7, 1957	*Makoszowy*, 504 nonmethane, class B	auxiliary	ignition of methane in a pillar crosscut	open light			1		
23	May 8, 1957	*Radzionków*, 504		explosion of water vapor and flammable fire gases	fire				10	
24	July 28, 1957	*Wujek*, 501		ignition of flammable fire gases and methane	fire					4
25	September 17, 1957	*Chorzów*, 501		explosion of flammable fire gases in a crosscut	fire		1			10
26	October 7, 1957	*Michał*, 501		explosion of flammable fire gases and of coal dust	fire		1			11
27	November 13, 1957	*Brzeszcze*, XXVIII west category III, class B	main	ignition of methane in the air heading	permitted explosive (special *Metanit*)	20			1	6
28	March 27, 1958	*Bobrek*, 413-414 category I, class B	auxiliary	ignition of methane in a roof cavity	open light	5			2	

Table 1.1 (continued)

1	2	3	4	5	6	7	8	9	10	11
29	May 5, 1958	*Niwka Modrzejów*, 501		explosion of flammable fire gases and of methane	unknown				4	
30	May 21, 1958	*Myslowice*, 501		explosion of flammable fire gases during hydraulic stowing operations	fire					5
31	June 9, 1958	*Siemianowice*, 510		epxlosion of flammable fire gases in the fire field	fire		5			10
32	March 8, 1958	*Rozbark*, 504		explosion of flammable fire gases during the packing of dams	fire					1
33	September 1, 1958	*Nowa Ruda* shaft 32 *Boleslaw* category III, class B	auxiliary	explosion of methane and of coal dust initiated in the rise gallery	safety lamp	500	14			
34	January 22, 1959	*Niwka*, 401 category I, class B	auxiliary	ignition of methane in the rise gallery	tobacco	25			2	
35	February 14, 1959	*Wirek* category I, class A	auxiliary	explosion of coal dust in a crosscut in the presence of coal	rock explosive (dynamite) in coal	40	1			
36	February 22, 1959	*Mszana* category III	main	ignition of methane in a locomotive shed	electricity				1	
37	April 8, 1959	*Moszczenica*, I category III	auxiliary	explosion of methane in the shaft during the shaft sinking operation	electricity	240	9		2	8

Table 1.1 (continued)

1	2	3	4	5	6	7	8	9	10	11
38	April 10, 1959	*Moszczenica*, IV category III	auxiliary	explosion of methane in the shaft during the shaft sinking operation	welding	30			1	1
39	November 24, 1961	*Polska*, 507 methane, class B	auxiliary	ignition of methane and of coal dust	tobacco		9			4
40	January 28, 1963	*Katowice*, 404/5 category I, class B		ignition of methane	open light (matches)			2		
41	June 27, 1964	*Moszczenica*, shaft *Moszczenica* I		explosion of methane	open light		1	3	3	5
42	August 14, 1964	*Bochnia*, salt mine category I		ignition and explosion of methane	open light (acetylene lamp)		4			22
43	January 6, 1965	*Sośnica* nonmethane, class B	main	local ignition of coal dust resulting from the detonation of the detonating fuse	prohibited destruction of detonating fuse in the presence of coal dust			3		
44	October 18, 1965	*Nowy Wirek*, 506 category III, class B	main	explosion of methane	short-circuit (electric arc) in a drill		1	3		1
45	April 22, 1967	*Walenty-Wawel*, 502 nonmethane, class B	main	coal dust explosion	shotfiring operations	350	4	3	2	10
46	July 23, 1968	*Niwka Modrzejów*, 510 category II, class B	auxiliary	methane and coal dust explosion	improper use of safety lamp	290	5	2		

the *Rozbark* mine (this mine at the time was called the *Heinitz* mine and was administered by Germany). As the result of this disaster 145 miners lost their lives [38]. The table does not contain any data pertaining to the period of the World War II since no statistics covering this period of time are available.

The following kinds of explosions are identified:

— explosions of firedamp alone,

— explosions of firedamp and coal dust in which methane initiated the explosion of coal dust,

— explosions of coal dust alone,

— explosions of flammable fire gases alone,

— explosions of flammable fire gases and coal dust in which flammable fire gases played the role of the initiator of the coal dust explosion.

Table 1.1. contains many a valuable information which makes it possible to summarize certain aspects. On the basis of this data a schedule was made (in Table 1.2) of the number of explosions resulting in human casualties in the period between the wars and after the World War II up to the year 1970. Explosions were discerned resulting in death of human beings and those resulting in other casualties; Table 1.2 refers to explosions, in which no life was lost, as "other explosions" in short.

According to Table 1.2 in the time from 1922 up to, and including, the year 1970 there were 47 explosions resulting in casualties to men; of these, 29 explosions included death casualties.

In the majority of explosions in which men lost their lives — in 21 out of 29 — coal dust had been one of the factors. This represents 72.4 percent of all explosions with death casualties. The least number of explosions in which human lives were lost is attributed to flammable fire gases — 10.6 percent of explosions with death casualties.

Considering all explosions ending in casualties to human beings, without differentiating the categories of such explosions, it can be ascertained that there were 53.2 percent of explosions without the participation of coal dust, and 46.8 percent of explosions in which coal dust participated. In other words the number of explosions with and without the participation of coal dust had been approximately equal.

The greatest number of coal dust explosions was initiated by explosions of firedamp. This is a rather obvious statement since methane is the easiest initiator of coal dust explosions. Explosions of other flammable fire gases can also easily initiate coal dust explosions but they are not so frequent as explosions of methane.

In Table 1.2 attention is drawn to figures showing the frequency of explosions of coal dust alone. In the period between the two world wars these explosions were caused by the use of rock explosives which, after

Table 1.2

A Schedule of Explosions in Polish Mines in The Years 1922–1970 in Which Men Were Injured and Killed

Years	Total number of explosions with casualties explosions with death casualties / other explosions	Explosions of coal dust alone explosions with death casualties / other explosions	Explosions of methane alone explosions with death casualties / other explosions	Methane and coal dust explosions explosions with death casualties / other explosions	Explosions of flammable fire gases alone explosions with death casualties / other explosions	Explosions of flammable fire gases and coal dust explosions with death casualties / other explosions
1922–1939	5/0	4/0	0/0	0/0	1/0	0/0
1945–1970	24/18	3/1	5/15	11/0	2/2	3/0
Total number of explosions	29/18	7/1	5/15	11/0	3/2	3/0
	47	8 (17.0%)	20 (42.6%)	11 (23.4%)	5 (10.6%)	3 (6.4%)

the World War I, were still, here and there, applied in the winning of coal.

In the postwar period there were two cases of coal dust explosions also caused by the use of rock explosives; but in both cases the manner in which these explosives were used had been contrary to regulations.

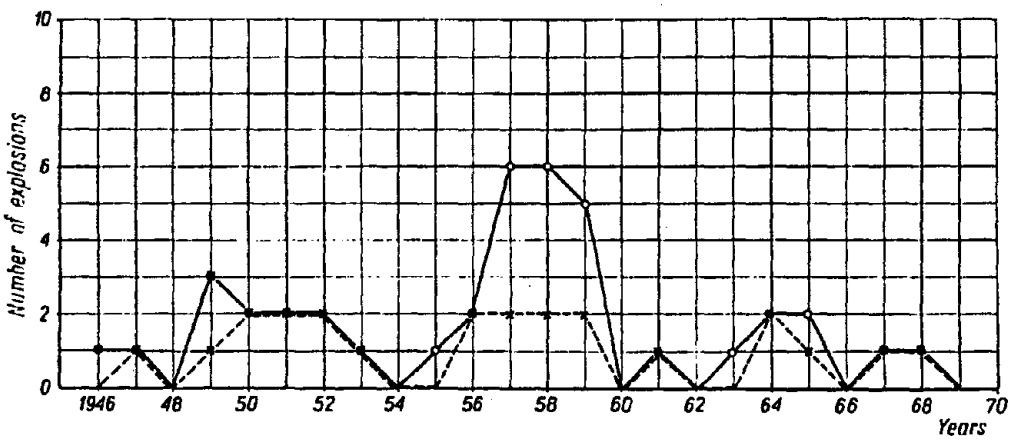


Fig. 1.1. A diagram showing the number of explosions in Polish mines: o — number of explosions with casualties; x — number of explosions with fatal casualtics.

The results included in Table 1.1 are graphically presented in Fig. 1.1.

On the basis of the data included in Table 1.1 the number of fatal accidents caused by explosions is shown in Table 1.3 for the period between the two world wars and for the postwar period up to the year 1970.

In Table 1.3 accidents are classified to show separately those caused by the explosion of firedamp alone, of coal dust alone, of flammable fire gases alone, of methane and coal dust, of flammable fire gases and coal dust. In the last-mentioned two groups coal dust explosions were initiated by explosions of firedamp or other flammable fire gases.

The total number of fatal casualties caused by explosions amounted to 240 men of which 77 men lost their lives in the period between the two world wars and 163 in the postwar period.

In relation to coal output there were 0.069248 cases of death per million tons of mined coal.

The higher number of fatal accidents — namely, 176 (73.3 percent) — was caused by explosions in which coal dust played a part.

Among the explosions in which coal dust participated the higher number of fatal casualties — 37.9 percent — was caused by explosions initiated through the explosions of firedamp.

On the other hand the lowest number of such casualties (8 percent) was caused by explosions of firedamp alone. It should be emphasized, how-

Table 1.3

A Schedule of the Number of Deaths Caused by Explosions in Polish Mines in the Years 1922–1970

Years	Total number of fatal accidents	Number of fatal accidents caused by explosions of coal dust alone	Number of fatal accidents caused by explosions of methane alone	Number of fatal accidents caused by explosions of methane and coal dust	Number of fatal accidents caused by explosions of flammable fire gases alone	Number of fatal accidents caused by explosions of flammable fire gases and coal dust
1922–1939	77	38	—	—	39	—
1945–1970	163	13	19	91	6	34
Total number of fatal accidents	240	51	19	19	45	34
Number of fatalities in proportion to the total number, %	100	21.3	8.0	37.9	18.7	14.1
1922–1939 Number of fatalities in proportion to the total number, %	100	49.4	0	0	50.6	0
1945–1970 Number of fatalities in proportion to the total number, %	100	8.0	11.7	55.8	3.7	20.8

ever, that this low index differs clearly from analogous statistical figures in other countries.

Figure 1.2, based on data included in Table 1.1, represents a graph showing the number of fatal casualties caused by explosions in the years from 1922 to 1970 and a graph showing the average number of fatal casualties in separate five-year periods.

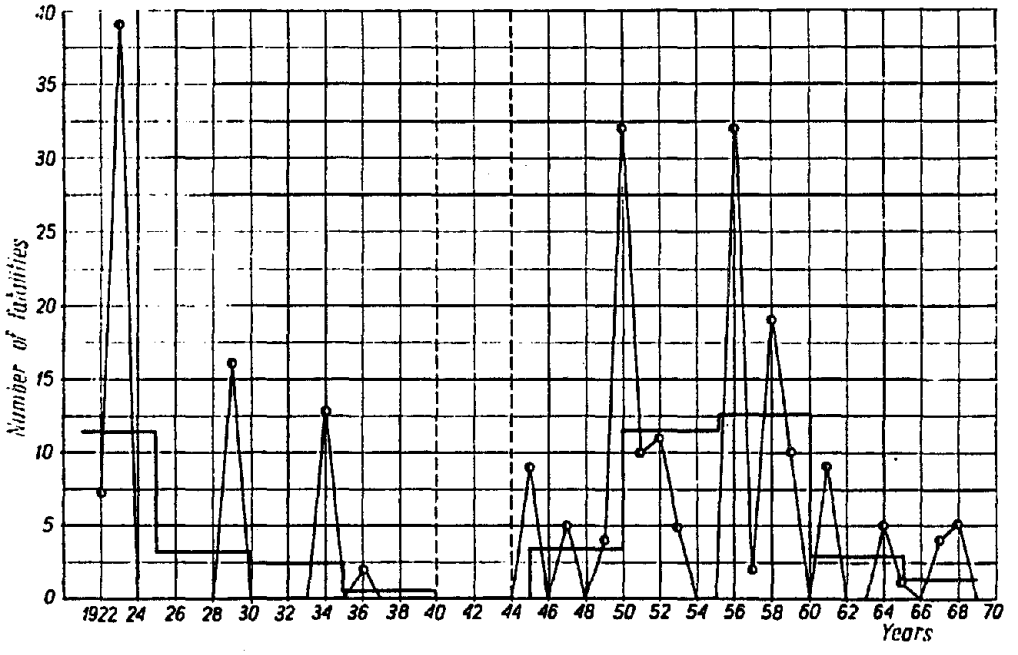


Fig. 1.2. A diagram showing the number of fatal casualties by explosions in the years from 1922 to 1970 and the average number of fatalities in particular five-year periods in Polish mines.

Figure 1.3 presents, in a graphic form, the number of fatal casualties in the years from 1922 to 1970 caused by:

— explosions without the participation of coal dust,

— explosions with the participation of coal dust.

On the basis of data included in Table 1.1 the Table 1.4 lists the causes of explosions which occurred in the whole period from 1922 to 1970. As can be seen from this table shotfiring, open light and electricity were, each of them, responsible for approximately the same number of explosions resulting in human casualties.

Yet this list does not give a true picture of the actual hazard. Under present conditions in mines open light is generally forbidden and, consequently, constitutes no danger. Furthermore, the total number of ex-

plosions dealt with in Table 1.1 being relatively small, the figures listed in Table 1.4 are not sufficiently representative. The rapid postwar progress in mining techniques in particular has changed the picture of hazards.

For instance, it ought to be emphasized that in the Polish mines no explosion has been registered initiated by friction resulting in human casualties though, of course, the hazard connected with such explosions increased considerably in view of the progressing mechanization of mining operations.

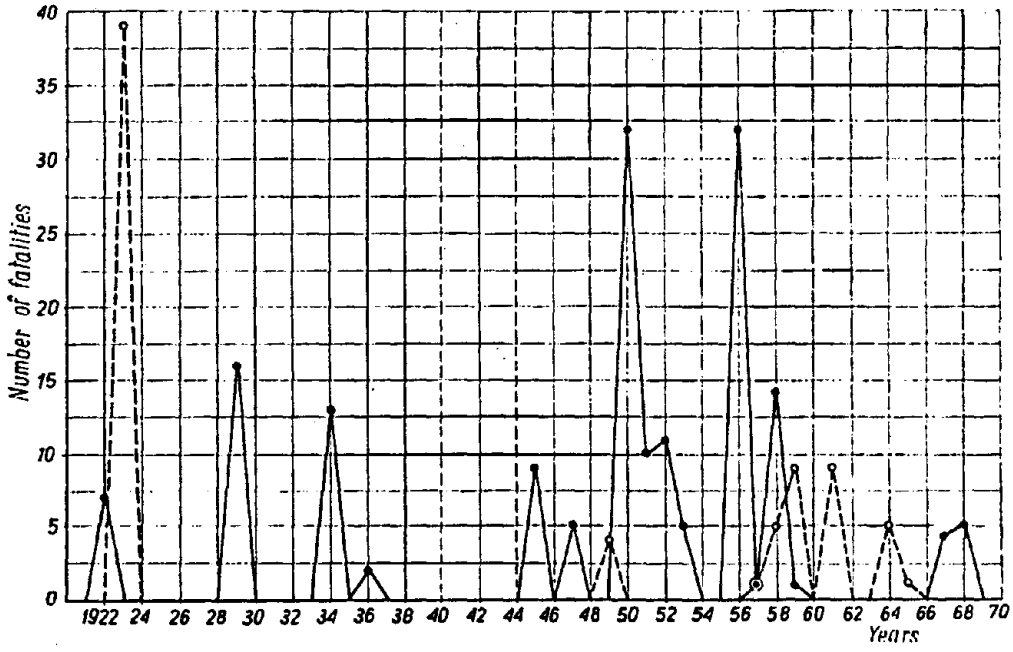


Fig. 1.3. A diagram showing the number of fatal casualties in Polish mines for the separate years from 1922 to 1969 caused by explosions with and without the participation of coal dust: --o— explosions without the participation of coal dust; --●— explosions with the participation of coal dust.

Considering that dangerous accumulations of methane represent a particularly serious hazard the type of ventilation used in mines must be an important factor in the problem of explosions. Unfortunately Table 1.1 does not throw any light upon this assertion. This is due, one should say, to the absence of precise statistical data. According to Table 1.1 the number of explosions amounted to:

— in the presence of auxiliary ventilation	15 (32.6%)
— in the presence of main ventilation	17 (37%)
— in the presence of unidentified ventilation	14 (30.4%)

Table 1.4

A Quantitative Schedule of the Causes of Explosions with Fatal Accidents to Men in the Period from 1922 to 1970

Specification	Shot-firing	Open light	Flammable fire gases	Tobacco smoking	Safety lamp	Electricity	Others
Number of accidents	9	10	6	5	2	9	5
Ratio to the total, %	19.6	21.8	13.1	10.8	4.3	19.6	10.8

When the above schedule is examined it should be remembered that ventilation of mines in the period directly following the war left much to be desired for reasons often enough discussed. It is being systematically improved, though, and this process of improvement is furthered also by the considerable progress in the methods of controlling the content of methane in the air of mines. Statistics of explosions in Polish mines discussed above could, in a certain measure, create a soothing impression particularly when the figures are compared with statistics of explosions in other coal mining countries. It ought, therefore, to be stated here quite emphatically that the potential danger of disasters due to explosions exists in Poland as much as it exists in other countries.

1.1.3. Statistics of explosions in foreign mines

According to the literature of the subject the oldest and the most accurate statistics concerning explosions are available in Great Britain. These statistics cover a very long period of time beginning with the year 1851. Very valuable publications of Tideswell [169], [170] as well as of Eisner and Tideswell [76] are the source from which the data given in this chapter is taken.

In Fig. 1.4 a diagram is presented showing the number of fatal casualties resulting from explosions in British mines in the years from 1880 to 1965.

The graph shows:

(a) the number of fatal casualties each year caused by all explosions and the number of disasters in which 100 persons or more lost their lives,

(b) the average number of deaths caused by all explosions in separate five-year periods,

(c) the number of major explosions responsible for casualties, shown under (b) above, in each of which 10 or more people lost their lives,

(d) the number of minor explosions responsible for casualties, shown under (b) above, in each of which less than 10 people lost their lives.

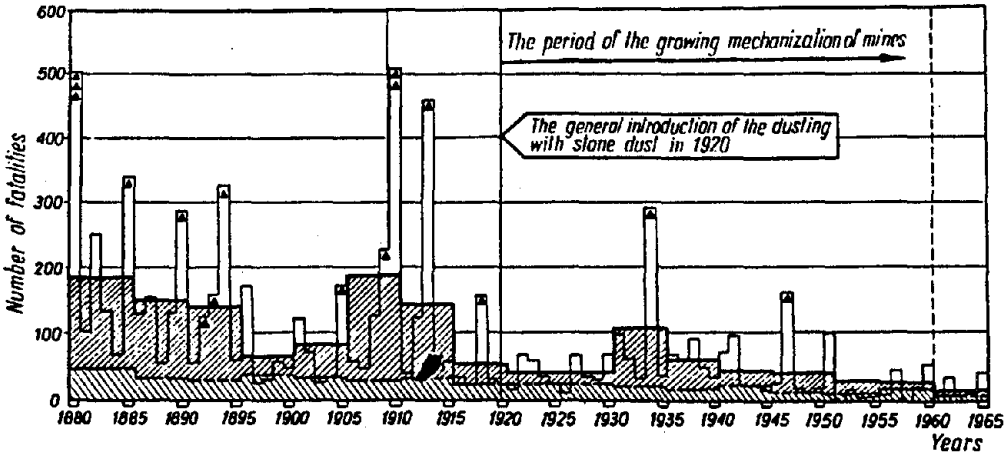


Fig. 1.4. A diagram showing the number of fatal casualties caused by explosions in British mines, by years, from 1880 to 1965 (after Tideswell): ⊓ — the number of fatalities in separate years caused by all explosions; ⊓ — exceptional mass disasters; the number of fatalities ⩾ 100; The annual average number of fatalities in five-year periods: ——— — all explosions; ///// — big explosions (10 and more fatalities); ▨ — small explosions (less than 10 fatalities).

In Fig. 1.5 a graph is given showing the number of great disasters for five-year periods from 1851 to 1965. An explosion in which 10 or more miners have lost their lives was considered a great disaster. The same diagram shows the average number of major disasters for the periods: 1851 to 1890, 1891 to 1920, and 1921 to 1960.

In Fig. 1.6 a graph is given showing fatal casualties resulting from great disasters for five-year periods beginning from 1881 up to and including the year 1965.

The same diagram shows the average annual number of deaths due to disasters for the periods: 1851 to 1890, 1891 to 1920, and 1921 to 1960. Moreover the annual average number of death casualties from a single explosion is given for the same periods of time. This average was regarded as the measure of the magnitude of the disaster.

All of the above named graphs speak for themselves very eloquently. Attention is drawn in Fig. 1.4 to the number of 14 great disasters in the years from 1880 to 1920, each responsible for the death of more than 100 people. In the period from 1920 to 1965 there were only two such disasters.

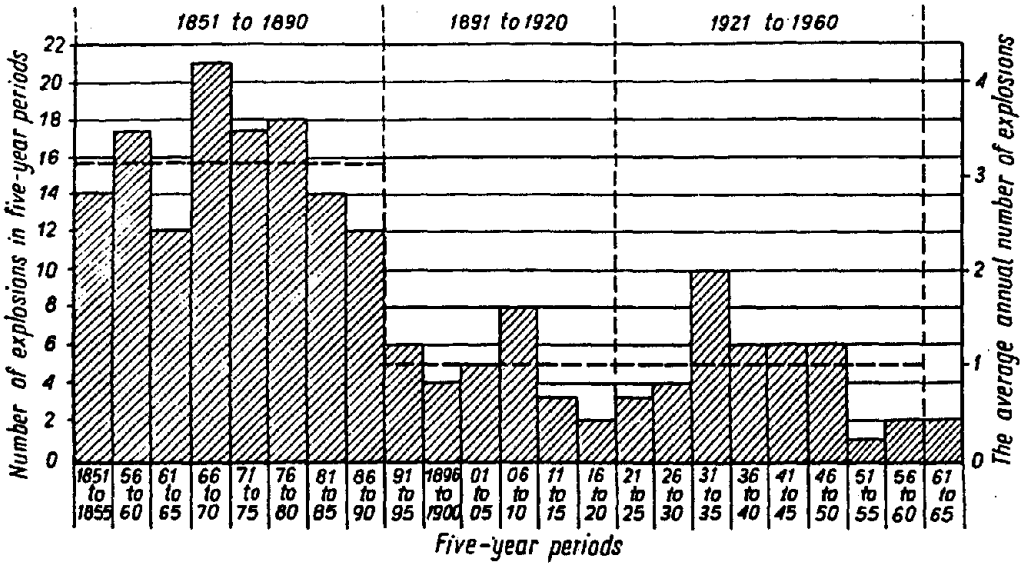


Fig. 1.5. A diagram showing the number of big disasters for five-year periods from 1851 to 1965 in British mines (after Tideswell): ///// — number of explosions in separate five-year periods; - - - - - — the average annual number of explosions.

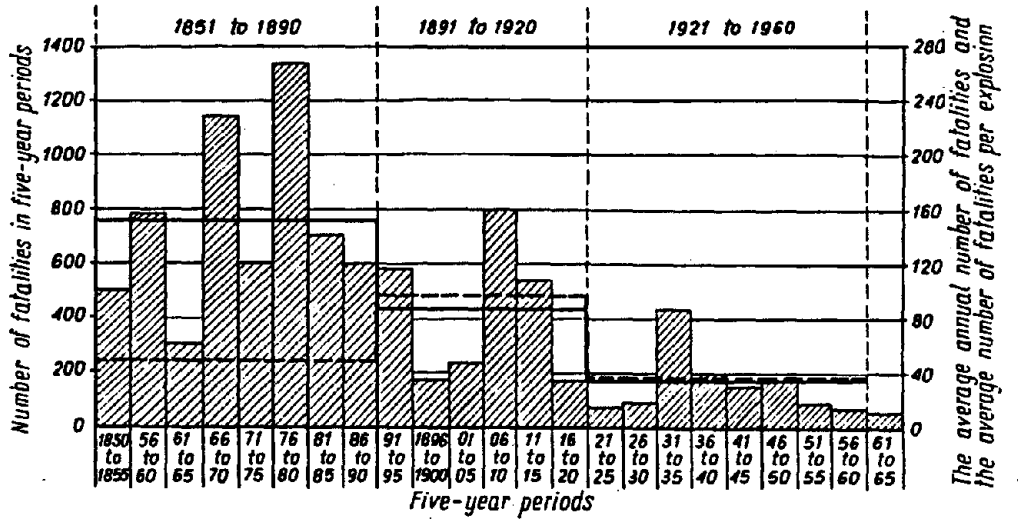


Fig. 1.6. A diagram showing the number of fatal casualties caused by big disasters in five-year periods from 1851 to 1965 in British mines (after Tideswell): ///// — number of fatalities in five-year periods: ——— — the average annual number of fatalities; - - - - - — the average number of fatalities per explosion.

The introduction in the year 1920 of the dusting of workings with stone dust has had, undoubtedly, its influence on the decline in the number of explosions as well as in their magnitude and, in consequence, on the

decrease in the number of casualties. The publications cited already do not give the number of death accidents. However, on the basis of the graphs shown in Fig. 1.4 it is possible to calculate that between the years 1880 and 1920 the approximate number of death casualties caused by explosions amounted in British mines to about 5300 which makes an average of 130 deaths per year. This, of course, is a tremendous number. On the basis of the same graphs (Fig. 1.4) it is possible to calculate the number of fatal casualties caused by explosions in the years 1921 to 1965 amounting to about 2030, or about 45 deaths per year. British investigators analyzed also shorter periods of time. These analyses show a considerable improvement in the conditions of safety as far as coal dust explosions are concerned. The diagram given in Fig. 1.7 [79] presents a very clear picture of

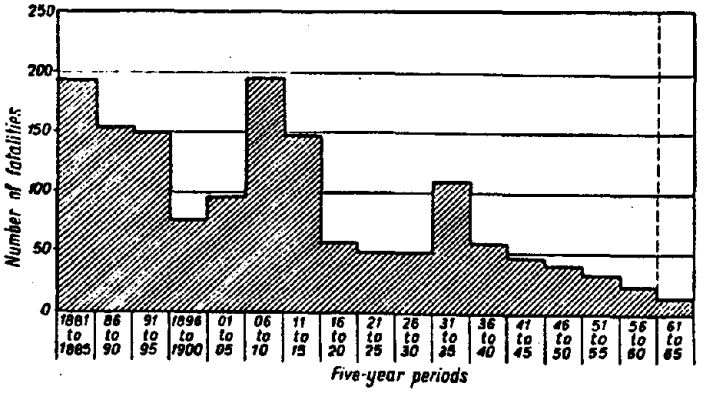


Fig. 1.7. A diagram showing the number of fatalities caused by all explosions in five-year periods from 1881 to 1965 in British mines.

the changes in the number of fatal casualties in five-year periods from 1881 to 1965. Attention is drawn to the irregularity in the decline of the death roll of disasters in the period between 1920 to 1961 caused by the great number of fatal accidents from 1931 to 1935. There occurred several great disasters in that period of time. After the year 1936, when very severe requirements were introduced concerning dusting with stone dust, there occurs a very regular decrease in the number of death accidents in separate five-year periods. This is illustrated in more detail by Table 1.5 containing a schedule of the number of all kinds of explosions in which lives were lost for five-year periods from 1936 to 1969. This table is given after H. S. Eisner and F. V. Tideswell [76].

Attention is drawn in Table 1.5 to a very significant decline in the number of explosions resulting in fatal casualties and a decline in the number of such casualties. However, up to the year 1965 the number of explosions in which coal dust played a part remained practically un-

changed. In general the number of fatal firedamp explosions decreased markedly since the year 1945. But the number of coal dust explosions, as mentioned already, remains unchanged. It should be emphasized that, according to British statistics, coal dust participates in explosions occurring in British mines to a lower degree than it does in Polish mines. According to our data firedamp explosions in workings, in which coal dust was present, in most cases did cause the initiation of coal dust explosions. It should be mentioned here that methods of investigating disasters in Poland are different from those employed in Great Britain. In the *EM Barbara* a special work had been carried out proving that after an explosion it is always possible to detect the participation of coal dust when samples of dust are examined under a microscope. Such examinations usually show the presence of coked grains even when lignite is concerned.

Table 1.5

A Schedule of the Number of Explosions with Fatal Accidents to Men in British Mines in the Years 1936–1969 Indicating the Number of Explosions in Which the Participation of Coal Dust Has Been Ascertained
(Deaths in Brackets)

Years	Number of explosions	Number of explosions excluding minor accidents	Number of explosions with the participation of coal dust
1936–1940	43 (306)	29 (287)	3 (172)
1941–1945	51 (224)	32 (199)	4 (79)
1946–1950	31 (211)	16 (172)	4 (152)
1951–1955	15 (129)	9 (116)	1 (81)
1956–1960	14 (123)	13 (122)	4 (76)
Total for years 1936–1960	154 (993)	99 (896)	16 (560)
1961–1965	8 (68)	8 (68)	3 (25)
1966–1969	1 (2)	1 (2)	0

In Great Britain a special commission [79] investigated especially the problem of coal dust explosions and considered the particulars of the quoted statistical data. The conclusions arrived at by the commission were that the introduction of the dusting with stone dust in 1920 undoubtedly not only suppressed a good many explosions, but also limited the range of those which occurred. However the commission found that, excluding particularly great disasters, the average number of fatalities caused by a single explosion did not diminish, to any considerable extent, in compar-

ison with the period from 1891 to 1920. This opinion seems to be perhaps unduly severe.

In Great Britain very accurate statistics are also kept of all cases of ignition of mine gases and of coal dust not merely of such ones which are connected with casualties among human beings.

Table 1.6 presents an analysis of registered cases of ignition in British mines showing their causes for the periods between 1936 and 1950 and between 1951 and 1958.

Table 1.6

An Analysis of the Registered Ignitions of Mine Gases and of Coal Dust in British Mines According to Their Causes

The cause of ignition	Number of ignitions in the years 1936–1950		Number of ignitions in the years 1951–1958	
	total	annual	total	annual
Open light	279	18.6	49	6.0
Tobacco	78	5.2	29	3.5
Electricity	72	4.8	33	4.0
Shotfiring	93	6.2	49	6.0
Frictional sparking	107	7.1	80	10.0
Safety lamps	18	1.2	3	0.5
Electric lamps	8	0.5	0	0
Fires	18	1.2	5	0.5
Miscellaneous	74	5.0	18	2.0
Total	748	50	266	23

It should be mentioned that cases of ignition caused by open light concern the mines in which open light was allowed.

Table 1.6 contains very interesting data. It can be seen, among other things, that the majority of ignitions were caused by friction. Since the periods included in Table 1.6 the danger of friction increased considerably as evidenced by the report of the Chief Inspector of Mines for the year 1968 [149] according to which out of 29 cases of ignition of gases in 1968, 21 were caused by friction (from the loading and cutting machines), 4 ignitions were caused by electricity and only 2 by shotfiring while the remaining 2 happened in connection with acetylene welding.

Of course not all ignitions initiate explosions resulting in casualties to human beings. Tideswell [169] states that between 1937 and 1953 for every 100 cases of ignition 40 percent caused no casualties, 44 percent caused casualties below the first category, and 16 percent caused fatal

accidents. While these statistics concern a period a long time past, yet they are worth mentioning.

As far as USA mining statistics are concerned the present author had the access only to data included in Humprey's publication [96] of 1959.

Figure 1.8 presents a graph showing the number of fatal casualties caused by firedamp and coal dust explosions in American mines during the years between 1870 and 1955. It should be stated, however, that the data concerning death accidents prior to the year 1910 is incomplete; it relates

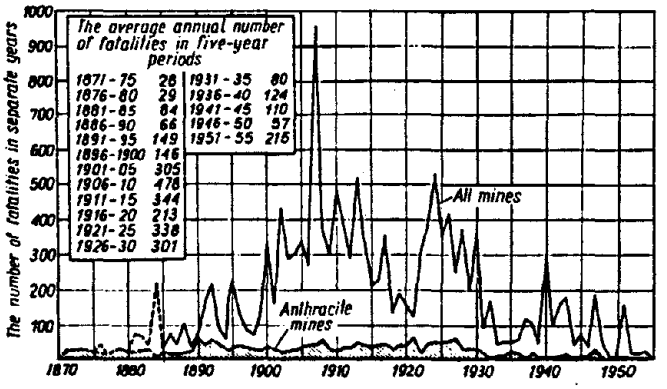


Fig. 1.8. A diagram showing the number of fatal casualties in explosions of methane and coal dust in American mines in the years from 1870 to 1955.

Note: statistics on the number of fatalities for the years prior to 1910 are not complete; they refer only to the States which were chief producers of coal. The Bureau of Mines was organized in 1910.

only to the States which are the main producers of coal. The Bureau of Mines, which is now responsible for the work on the safety in mines and for statistics of casualties, was organized in 1910. The graph, therefore, shown in Fig. 1.8 can serve only as a means of a general orientation. Nonetheless it illustrates the fatal consequences of explosions in American mines just as the previously discussed British statistics illustrated the situation in British mines.

On the basis of data obtained from the same source Table 1.7 shows the average annual number of fatal casualties caused by explosions in American mines for five-year periods.

The quantitative schedules of ignitions of gases and of coal dust for two periods of time showing their causes, as presented in Table 1.8, have also been compiled on the basis of data published by Humprey.

Though the data given in the last mentioned table does not illustrate the actually existing hazard, as far as the causes of explosions are concerned, since the progress in the exploitation techniques in American

Table 1.7

A Schedule of the Average Annual Number of Fatal Accidents Caused by Explosions in American Mines

Period	Average annual number of death accidents	Period	Average annual number of death accidents
1871–1875	28	1916–1920	213
1876–1880	29	1921–1925	338
1881–1885	84	1926–1930	301
1886–1890	66	1931–1935	80
1891–1895	149	1936–1940	124
1896–1900	146	1941–1945	110
1901–1905	305	1946–1950	57
1906–1910	478	1951–1955	36
1911–1915	344		

Table 1.8

A Schedule of the Causes of the Ignition of Mine Gases and of Coal Dust in American Mines

Causes of ignitions	Years 1941–1950		Years 1951–1958	
	number of ignitions	percentage of the total number of ignitions	number of ignitions	percentage of the total number of ignitions
Open light and tobacco	114	46	34	20
Shotfiring	60	24	37	22
Safety lamps	14	5	5	3
Fires	2	1	3	2
Electricity	59	24	71	43
Friction	—	—	16	10
Total	249	100	166	100

mines is a very rapid one particularly in the field of the mechanization, yet the information deserves to be included here.

A feature which attracts attention is the decidedly highest percentage of ignitions caused by electricity amounting to as much as 43 percent.

According to information supplied directly by scientific workers of the Bureau of Mines at international conferences of the Safety in Mines Research Establishments the number of firedamp ignitions in American mines, caused by friction, increased considerably.

It is known that in American mines coal cutter machines such as, for example, continuous miner, are gradually used. With very quick face

advance and with considerable fineness of coal of methane seams the emission of methane is very intensive so that at the very face it is impossible to avoid a rather frequent appearance of explosive firedamp mixtures. These mixtures are often ignited by friction when the working elements of the machine strike against sandstone or inserts of piryte. In consequence the danger of initiating explosions by friction grew in American mines as it did in British mines of which a mention had already been made.

In connection with the very rapid progress of the exploitation techniques the hazard of firedamp and coal dust explosions undergoes quick modifications as far as the initiators of such explosions are concerned. A good illustration of this fact is given exactly by the increase in the number of ignitions of methane caused by friction.

Unfortunately the exchange of statistical information about explosions between coal producing countries leaves much to be desired. The more laudable, therefore, is the practice of such countries which publish this important and very informative data as, for instance, the British mining authorities do. As it is, the statistical information to which the present author had the access are only partial. On this basis Table 1.9 lists explosion disasters in each one of which not less than 30 human lives were lost, the time period covered extending from 1930 to 1960.

The total number of the lives lost in the above disasters in separate countries is also given in Table 1.9.

It ought to be emphasized that this horrifying number of fatal casualties (9443) caused by disastrous explosions between the years 1930 and 1960 covers only the disasters in which more than 30 human lives were lost. Moreover this depressing figure is not complete particularly because not all of the coal producing countries are included in it.

The present author obtained also information about explosion disasters in the period between 1900 and 1951 in each of which at least 50 men were killed. This data is listed in Table 1.10.

The tremendous number of lives lost in these disasters (20,448 people killed) — more serious than the ones dealt with in Table 1.9 — is again incomplete since the data does not cover all coal producing countries.

Of course the number of fatal casualties, resulting from explosions which occurred in the time periods covered by Tables 1.9 and 1.10, is much higher also because these tables account only for major disasters in each one of which not less than 30 or 50 men were killed.

The number of explosions resulting in a lower individual number of death accidents is undoubtedly much larger than the number of major disasters, and the total casualties suffered exceed those resulting from major disasters as can be seen clearly in the most accurate statistics kept in Great Britain.

Table 1.9

A Schedule of the Number of Explosion Disasters
and of the Number of Death Accidents in the Separate Coal Mining Countries
in the Years 1930–1960
(the schedule comprises only such disasters in which at least 30 men were killed)

Country	Number of explosion disasters	Total number of men killed
Belgium	3	124
Canada	2	84
France	2	97
Germany	13	1257
India	6	597
Italy	2	228
Manchuria	1	1527
Japan	40	3258
Spain	1	34
Great Britain	11	879
United States	16	996
South Africa	7	362
Total	104	9443

Note: Poland does not appear on the above list because, in the period of time named, in the most serious disaster in the *Jankowice* mine in the year 1950 — 29 miners have lost their lives.

Table 1.10

A Schedule of the Number of Explosion Disasters
and of the Number of Death Accidents in the Separate Coal Mining Countries
in the Years 1900–1951
(the schedule comprises only such disasters in which at least 50 men were killed)

Country	Number of explosion disasters	Total number of men killed
Belgium	3	445
Canada	2	189
France	3	1243
Germany	13	2081
Italy	1	185
Manchuria	1	1527
Japan	43	6604
Great Britain	17	2345
United States	52	5829
Total	135	20,448

Irrespective of the inaccuracies pointed out above the two tables discussed present a tragically convincing picture not only of disasters, which had taken place in the past, but also of the potential danger of explosions in coal mines at the present time.

This statement is corroborated by numerous explosion disasters which occurred in the years from 1960 to 1970. Accurate world data for this period is not available; according to published information more than 3200 miners were killed in explosions. Actually this number is much larger.

Too much space would be needed to mention here all disasters of which the data was published in the above named period of time. But the following ought to be listed here as tragic examples of the danger: the firedamp and coal dust explosion in 1962 in the *Luisenthal* mine in the Federal Republic of Germany in which 299 miners were killed; the coal dust explosion in 1963 in the *Mikawa* mine in Japan resulting in the death of 457 miners; the firedamp and coal dust explosion in 1965 in the *Yamano* mine in Japan — 331 fatal casualties; the firedamp and coal dust explosion in 1965 in the *Bhori* mine in India — 306 death accidents; the explosion in 1965 in the *Orasi* shaft in Yugoslavia — 144 men killed; the methane explosion and fire in 1968 in the *Farmingthon* mine in the USA — 78 men killed; the explosion in 1970 in the *Breza* mine in Yugoslavia — 51 death accidents.

1.2. FORMATION OF COAL DUST IN MINES

1.2.1. The definition of coal dust

Coal dust, regarded from the viewpoint of its explosibility, is the name used for the fractions of comminuted coal which take part in the explosion. This is the most general definition.

Coal is not, obviously, an individual chemical compound. There are serious differences between separate seams in which coal has varying properties. Quite serious differences depending upon the age of coal actually demand that, if one wished to be very precise in formulating the definition of coal dust from the point of view of its explosibility, one would have to determine — for various kinds of coal — the limit fineness below which particles of coal actively participate in explosions. This approach to the problem, however, would create great practical difficulties in all experiments conducted on a large scale and also in the utilization of the results of such experiments in the mining practice.

As the result of experiments carried out in the course of many years it can be possible to regard as coal dust — in problems concerning its

explosibility — the fractions of comminuted coal which pass through a sieve of 1 mm mesh.

In all investigations carried out in the *EM Barbara* the coal dust used answered the above definition.

1.2.2. The causes of the formation of coal dust in mines

Exploitation of coal seams is inseparable from the formation of coal dust. Only through underground gasification of coal is it possible to utilize coal seams without producing coal dust. The present way of the extraction of coal makes the formation of coal dust unavoidable.

Coal dust is formed in mines in the course of the winning, loading and transporting of coal. Furthermore, large quantities of coal dust are produced through the crushing of coal by the rock pressure.

The above mentioned causes of the formation of coal dust are bound up with normal technological processes. Apart from these, large quantities of coal dust might be formed in a short space of time as the result of rock burst and sudden coal and gas outburst.

1.2.3. Information about the quantities of coal dust formed in mines

The ease with which coal dust is formed depends on the physical properties of coal; soft coals produce larger quantities of dust than hard coals.

In the normal technological processes the largest amounts of coal dust are produced in the course of the winning of the coal. These quantities of coal dust differ considerably depending on the method of winning. When combined cutter loaders are used more coal dust is produced than in the course of winning coal by shotfiring with the use of explosives. When explosives are replaced, for example, by the Armstrong method (that is, the use of compressed air) the formation of coal dust becomes much smaller.

Combined cutter loaders actually used produce from 0.8 to 1.2 percent of coal dust. Less than that — about 0.7 percent — is produced by plows.

Hurysz [97] carried out very interesting investigations on the causes of the formation of fine coal in the output. In his work he determined also the percentage of coal dust in the output. This author found that the content of coal dust in the output varied greatly depending on the type of the coal and on the method of coal exploitation from the seam, in particular.

The quantities of coal dust in the output from the seams 413 to 504 amounted to (in percentages):

from 2.89 to 5.56 in roadways,
„ 2.48 „ 4.11 in longwall faces,
„ 1.73 „ 4.42 in pillars.

Hurysz gives also the following results of his investigations in one of the collieries: about 50 percent of fine coal are produced in the course of the winning of coal, about 13 percent in the course of transportation and about 37 percent in the course of mechanical preparation. Unfortunately the work of Hurysz dates from the year 1950 and, therefore, does not characterize accurately the present conditions of the formation of coal dust at the mine face.

Apart from the above mentioned work of Hurysz the present author never came across a publication in which information could be found about the amounts of coal dust produced in the course of all underground technological processes in mines, which use all the modern technical equipment, and methods of winning coal as well as modern exploitation and transportation systems.

As far as the transport of coal is concerned there are very big differences in the quantities of coal dust produced depending on whether pans, shaker, flight and belt conveyors are used. Even if the same type of conveyors is used there are considerable differences between the quantities of coal dust left in the workings depending on the condition of the conveyor. As an example, it can be said that in one of the mines the carrying of one ton of coal over a distance of 100 m by a belt conveyor resulted in the deposition of 0.6 kg of coal dust in the belt-conveyor road. In another mine this amount reached 0.8 kg. But in a mine in which the belts were tightened the quantity of coal dust, left after the transportation of 1 ton of coal over the distance of 100 m, amounted to 0.042 kg only. Nevertheless the spraying with water at transfer and discharge points also plays an important role.

The entire problem of the quantitative study of coal dust formation — under conditions created by diverse methods of mining, loading and transportation of coal under actual conditions in mines — would have required a special labor consuming investigative effort. The data now available on this subject is rather fragmentary.

It is possible to determine the amount of coal dust in the output of a mine when the yield of fine coal in the output, and the average percentages of coal dust in the fine coal are known. In relation to the problem of the explosibility of coal dust the most important is to know the quantity of dust which remains underground. This question is, therefore, the one which deserves an examination more than anything else.

According to Soviet data the quantity of coal dust which remains underground oscillates between 0.25 and 3 percent of the total output.

The actual yield of fine coal from our mines of hard coal amounts to: in the case of the power coal:

10–0 mm	40.5%
6–0 mm	30.4%

in the case of the coking coal:

10–0 mm	55.0%
6–0 mm	42.0%

The following percentages of coal dust are formed: in the roadways 20.4; in pillars — 12; and in longwalls — 8.6. These figures are the actual average values from the entire hard coal industry.

From the above data it is possible to estimate the approximate quantities of coal dust produced. For the five examined mines the content of dust in fine coal amounted to from 19 to 41 percent (data supplied by the Mechanical Preparation Department of the Central Mining Institute — GIG).

The amount of coal dust remaining underground — that is, of coal dust creating the danger of explosions, can be considerably diminished by various methods which will be discussed in later chapters. These methods, it should be said, may be reduced to limiting to the minimum the fineness of coal and depriving coal dust of its dispersibility thereby restricting the dispersion of the dust and making it possible to remove it from the mine together with the output. This is very important both from the viewpoint of the reduction of the hazard of coal dust explosions, and from the economical point of view.

1.3. BASIC PHENOMENA BOUND UP WITH THE FORMATION AND DEVELOPMENT OF COAL DUST EXPLOSIONS AND THE FUNDAMENTAL EXPLOSION FACTORS

1.3.1. The formation and development of coal dust explosions

The phenomena which occur at the formation and development of a coal dust explosion are discussed in sufficient detail in the separate chapters of this book. However, to make easier the discussion of the basic parameters of coal dust explosions it is desirable to describe, first of all and in the simplest way, the course of a coal dust explosion.

The basic conditions which are needed to initiate a coal dust explosion are the formation of a coal dust cloud and its ignition.

Normally, under conditions prevailing in mines, coal dust accumulates on the surfaces in the workings while the quantities of this dust in the air are entirely insufficient to develop an explosion; in other words they are much lower than their lowest explosive limits.

Two factors must act synchronously to initiate a coal dust explosion: a factor which will cause the raising of a dangerous cloud of coal dust and the appearance, at the same time, of a thermic factor capable of igniting this cloud.

Such conditions are created in mines most easily when a local explosion of firedamp occurs or when shotfiring operations are conducted.

A local explosion of firedamp causes a strong blast of air as the result of the expansion of the hot products of the combustion of methane. This blast can easily raise a cloud of coal dust if the dust is sufficiently dispersible. At the same time the burning methane can easily ignite this cloud which we may call the primary cloud. In this way the conditions of the initiation of a coal dust explosion are easily fulfilled in a case of a local methane explosion.

A similar phenomenon might occur as the result of shotfiring.

During a detonation of an explosive a shock wave is produced in the face followed by a blast of air together with the products of the detonation. The velocities of the shock wave and the blast of air decrease as the waves move away from the face (for example, at the distance of 25 cm from the outlet of the shothole they amount to about 800 and 600 m/sec, respectively; at that of 35 cm — about 400 and 200 m/sec). The above figures are given as an example and they relate to concrete specified conditions.

As a result the blast of air created by shotfiring can, just as easily as the explosion of methane, raise a dangerous cloud of coal dust. If the explosive used is not sufficiently safe in the presence of coal dust the flame of the detonation might ignite the raised cloud of coal dust. In this way shotfirings also synchronize very well the raising of a cloud of coal dust and the appearance of the thermic factor capable to ignite the explosive medium.

The combustion of coal dust in the primary cloud causes a sudden liberation of thermal energy. The combustion products of coal particles have a high temperature and, in consequence, they expand raising in turn the next cloud of coal dust which may be called a secondary cloud. The combustion of coal dust in the primary cloud extends to the secondary cloud causing a reinforcement of the blast and the raising of the next cloud of coal dust. If, in a given working, the accumulated coal dust is sufficiently dispersible the described phenomenon becomes continuous in its character and coal dust explosion can develop. This type of the development of coal dust explosions is called the propagation of explosion. Explosions can propagate themselves over very long roads depending on the kind of the coal dust deposited in the consecutive workings.

It follows from the above elementary description of the course of a coal dust explosion that the development of such an explosion needs a sufficiently strong blast wave to raise dangerous clouds of coal dust in which a flame develops. Thus in coal dust explosions the front of the blast always keeps ahead of the flame. This is easily seen when one

observes explosions of coal dust in experimental galleries on the surface. An experimental gallery of this kind, existing in the *EM Barbara*, is shown as an example in Fig. 1.9.

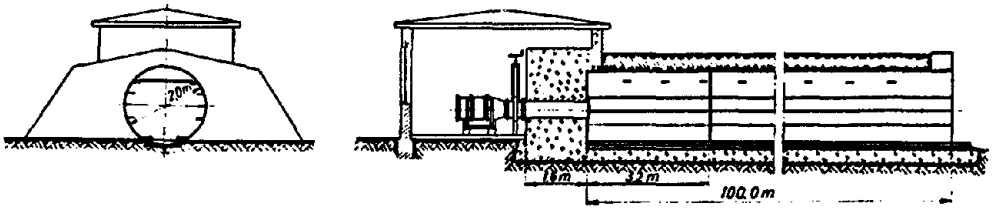


Fig. 1.9. The 100 m surface experimental gallery in the *EM Barbara*.

When the experiment is being carried out in the gallery a quantity of coal dust sufficient to explode is distributed along the gallery on the floor or on shelves. At the face of the gallery a steel mortar is placed with a groove loaded with a rock explosive. Shotfiring of this explosive causes the formation of the primary cloud of coal dust and its ignition. Next, the ensuing explosion is propagated along the entire gallery. Then at the outlet of the gallery it is possible to observe the escape of the cloud of coal dust and behind the front of this cloud the appearance of the flame.

Figure 1.10 presents a photograph of an explosion in the experimental gallery.

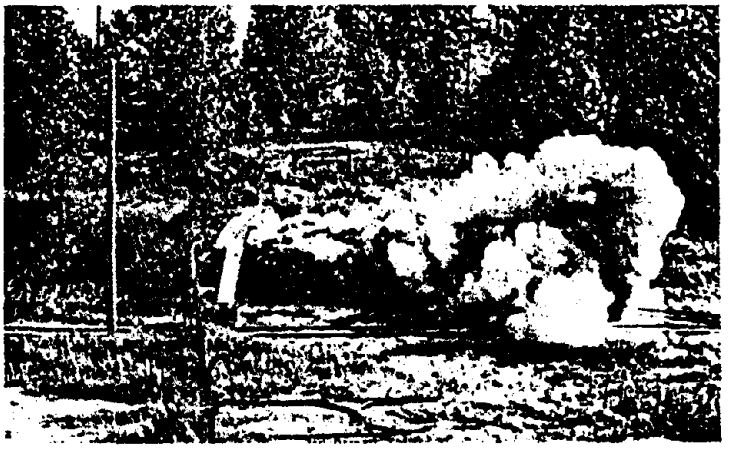


Fig. 1.10. A jet of a coal dust explosion from the 100 m surface experimental gallery of the *EM Barbara*.

1.3.2. A list of factors on which depends the possibility of a coal dust explosion and its course

The possibility of coal dust explosions and their development is

a function of a series of variable factors which are hereafter called, for short, explosion factors. These factors are the following:

- explosibility of coal dust,
- dispersibility of coal dust,
- the degree of fineness of coal dust,
- limits of coal dust explosibility,
- the initiation of the explosion,
- conditions of dispersion,
- the range of the dustiness of workings and the distribution of coal dust in workings,
- the presence of methane in the air,
- conditions of workings.

2. BASIC INFORMATION ABOUT THE EXPLOSIBILITY OF COAL DUST

The explosibility of coal dust can be investigated on a mine or on a laboratory scale. The two forms of investigations differ very materially from each other.

2.1. INVESTIGATIONS ON THE EXPLOSIBILITY OF COAL DUST ON A MINE SCALE

Investigations concerning the explosibility of coal dust consist in determining its capability of propagating explosions.

Coal dust in mines is dangerous only if it is capable of propagating explosions. Such a coal dust is called dangerous. When coal dust is incapable of propagating explosions it is referred to as safe coal dust.

The capability of coal dust for propagating an explosion is examined in surface experimental galleries such as the one shown in Fig. 1.9, or in experimental underground galleries such as, for example, exist in the *EM Barbara* (Fig. 2.1).

Experimental galleries are described in the GIG (Central Mining Institute) Reports [21], [42], [43].

Investigations on the capability of coal dust to propagate explosions have to be carried out in fixed conditions — that is, with the use of a specified initiator of the explosion, with a specified distribution of coal dust in the gallery in quantities most favorable for the development of an explosion. Examining the coal dust in such fixed conditions over a determined length of the experimental galleries one finds whether the flame of the explosion passes over the entire zone, in which coal dust had been distributed, or fades before reaching the end of the zone. In the first case it is recognized that the coal dust was capable of propagating an explosion; in the second — the conclusion is that the coal dust was incapable of propagating an explosion. Such an investigation allows only to determine the capability, or incapability, of the coal dust in question of propagating an explosion. Ordinarily, however, this does not suffice.

To specify more precisely the explosibility of coal dust the experiments have to be carried out on broader lines.

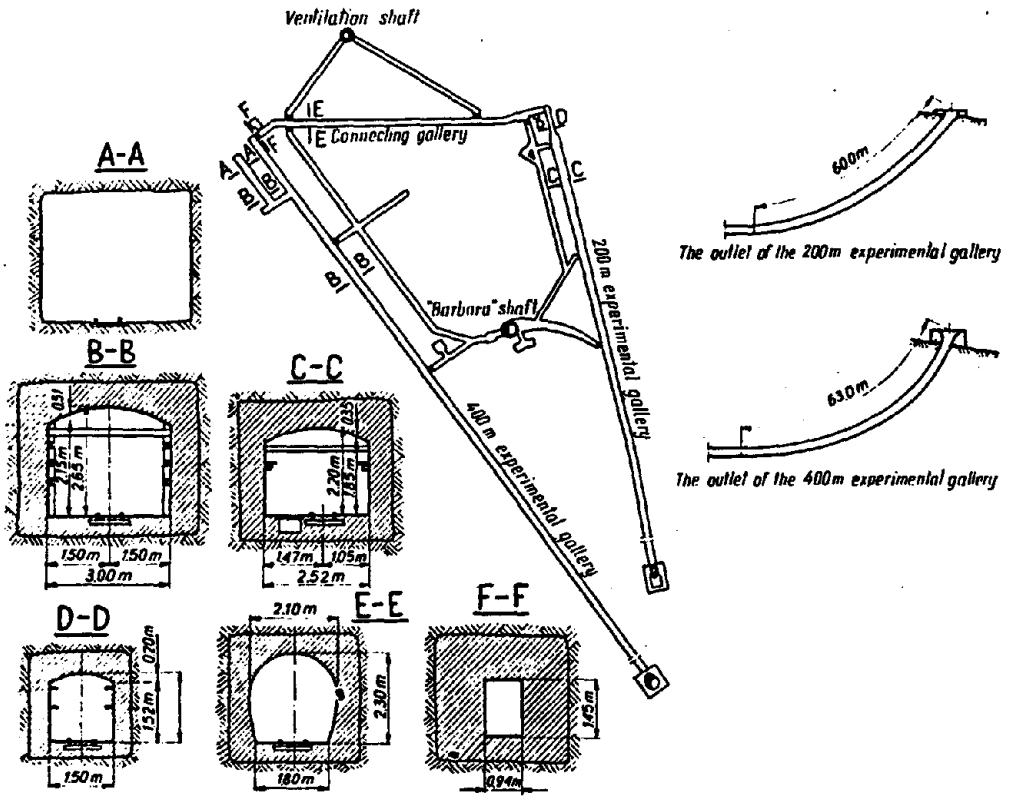


Fig. 2.1. Underground experimental galleries in the *EM Barbara*.

2.1.1. The degree of the explosibility of coal dust

The degree of the explosibility of coal dust is measured by establishing the percentage of incombustible solid matter which should be contained in the dust in order to make it incapable of propagating an explosion.

In the course of the experiments various quantities of standard stone dust (usually limestone dust) are added to a given kind of coal dust and, as the result of a number of experiments, the percentage of the content of incombustible solid matter is established which makes the mixture incapable of propagating an explosion. This limit content of the incombustible solid matter can be determined with a varying degree of accuracy.

The content of incombustible solid matter in coal dust is denoted by the symbol n.

The incombustible solid matter consists of the natural incombustible matter — that is, of the ash and the hygroscopic water, and of the stone dust if it is added to the natural coal dust. When coal dusts containing

free water are examined the water content is specified separately and is denoted by the symbol W_k.

The limit value of n, with which the dust is incapable of propagating an explosion, is denoted by the symbol S. Thus it represents the measure of the degree of explosibility of a given coal dust under specified experimental conditions.

In the investigations carried out in the *EM Barbara* the value S is being determined with an accuracy up to 2.5 percent which means that when it is established that a given coal dust is not capable of propagating an explosion, with $n = 70$ percent, then should n be equal to 67.5 percent the dust in question can propagate an explosion.

The accuracy in establishing the values of S depends upon the number of tests carried out with n percent of incombustible matter content in the dust with which this kind of dust did not propagate explosions. A conclusion based, for example, on two negative experiments only would not guarantee sufficient accuracy. Depending on the degree of accuracy we try to attain in establishing the values of S, we have to rely on a correspondingly larger number of experiments with negative results. The accuracy of the established value of S is shown by indicating the number of experiments carried out in which the value S sufficed to safeguard against the propagation of an explosion. This number is placed as a subscript to the symbol S, for example: S_3, S_5, S_{10}, etc.

The above described way of investigating the degree of the explosibility of coal dust in the surface and underground experimental galleries, under conditions approaching natural conditions in mines, is the most widespread way of carrying out such investigations. When investigations must give very precise results much more numerous experiments are made in which the frequency of the cases with propagated explosions is being determined for various values of n. If the experiments are being conducted carefully enough it is found that the distribution of frequency with which explosions are propagated, at various values of n, is a normal distribution and, consequently, with the aid of a statistical analysis it is possible to establish the value of S with the desired degree of probability. The confidence limit of this determination can also be established.

Investigations of this kind are very labor consuming and were conducted in the *EM Barbara* when works of a fundamental importance were carried out.

Investigations conducted in experimental galleries on a large scale are labor consuming and expensive. During these experiments, however, a lot of information is obtained necessary for the characterization of the course of an explosion such as the range of the flame, its velocity in the consecutive sections of the gallery, its duration, and the dynamic and static

pressure at particular measuring stations. Methods of measuring these magnitudes were published in the GIG Report [107].

The distances between the measuring stations are variously fixed, namely, at 10, 20 and 40 m. The stations are connected by the cable with recording devices installed in the laboratory on the surface.

2.1.2. The index of the explosibility of coal dust

Apart from the degree of the explosibility of coal dust, denoted by S, the so-called explosibility index Z is also determined

$$Z = \frac{S}{100 - S} \tag{2.1}$$

This index shows the weight amount of the incombustible solid matter per weight unit of pure coal dust necessary for protecting it against propagation of explosion. The index in question is a very useful and practical measure of the explosibility of a given coal dust and plays an important role in calculations which will be discussed in subsequent chapters.

The degree of the explosibility of coal dusts S, as well as the indices of the explosibility Z, will be discussed in detail when the pertinent parameters of the explosibility of coal dust will come up for consideration. It ought to be mentioned here only that for the dangerous coal dusts, which are produced by the majority of coal seams exploited in Poland, the values of S are very high sometimes exceeding even 80 percent which means that the value of Z might amount to more than 4.

2.1.3. Methods of measuring the parameters of coal dust explosions in the experimental galleries of the *EM Barbara* [107]

2.1.3.1. General information. Investigations on the explosibility of coal dust on a mine scale are carried out in experimental galleries discussed in Section 2.1.

Very important elements of experimental galleries are steel roof bars fixed every 3 m, steel lateral shelves along the sidewalls, and recording stations shown in Fig. 2.1.

The main source from which the knowledge about coal dust and firedamp explosions is derived are experimental explosions carried out on a large scale in galleries especially adapted for this purpose simulating workings of real mines. The effectiveness of these investigations, conducted at considerable expense, depends in the first place upon the quality of the equipment installed in the experimental galleries and upon the

proper choice of the methods of measuring the basic parameters of explosions.

To the most important magnitudes which both qualitatively and quantitatively determine the course of a coal dust and firedamp explosion the following should be counted:

— the velocity of propagation of the front of the explosion flame,
— duration of the flame,
— the range of the flame,
— the static and dynamic pressure,
— the velocity of the propagation of the front of the blast.

For determining the three first mentioned magnitudes two parallel measuring methods are used in the *EM Barbara*, namely:

— the method of detonators,
— the photoelectric method.

The oscillograms, obtained during the time in which an experimental explosion takes place, make it possible to determine the velocity with which the front of the explosion flame propagates, the duration of the flame at particular recording points, and the range of the flame. The remaining magnitudes are found when the static dynamic pressure is measured by two independent measuring systems.

2.1.3.2. Measurement of the flame velocity by the method of detonators. At measuring stations, located at intervals of 10 or 20 m, sets of special detonators called recording detonators are placed. The lower part of these detonators is filled with a neutral material, while their upper parts contain lead azide with lead trinitroresorcinate which fills the detonators up to 3 man below the edge of their cases. Ten detonators are placed in special grips on the circumference of every measuring station. All detonators of every measuring station are interconnected by one common cable coiled round each detonator. The cable is a part of the measuring circuit composed of an amplifier of a 16-pen chronograph, and of the source of the current.

A scheme of the measuring system is shown in Fig. 2.2.

Before the experiment begins electric current flows through the measuring circuit causing a deviation of the chronograph pen from the zero position. The speed with which chronograph paper moves is 20 cm/sec. When the front of the flame reaches the measuring station the measuring circuit is broken by the first exploding detonator. Simultaneously the chronograph pen returns to the zero position. The time when the flame reaches particular measuring stations is registered in this way in the form of a steplike series of marks, the distance between which denotes the time of the passing of the front of the flame from one measuring station to the next. When the time and the distance between the measuring stations is

known it is possible to calculate the average velocity of the flame between the neighboring measuring stations.

The course of the breaking of measuring circuits is registered also by a 16-channel tape recorder so that the reliability of the measuring process becomes more certain. The oscillograms so obtained also show the range of the flame.

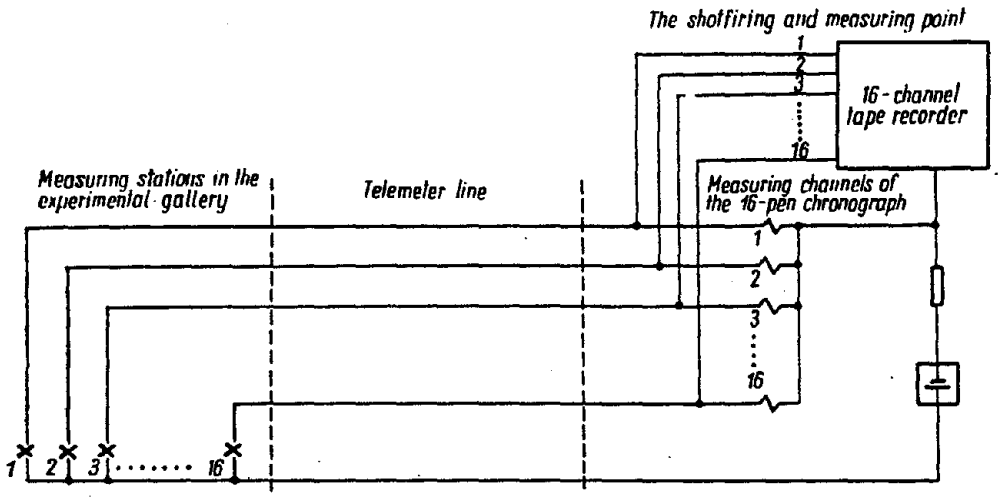


Fig. 2.2. A diagram of the flame velocity measuring system by the method of detonators.

2.1.3.3. Measurement of the flame velocity by the photoelectric method. In the photoelectric method the light-dependent resistors, located at every measuring station in special steel settings, serve as flame detectors. Each measuring station is equipped with three light-dependent resistors in settings placed one above another.

2.1.3.4. Comparison between the detonator method and the photoelectric method. In view of the fact that two distinct measuring methods were employed it was thought advisable to find out whether these methods show any regular differences in the results obtained, or give approximately identical results. In the latter case any observed differences would have been only of random character

$$\log y = \alpha + \beta \log x \qquad (2.2)$$

where

y — the variable of the time measured by the detonator method,

x — the analogical variable obtained by the photoelectric method.

Parameters α and β are constants determined by the method of the least squares. The logarithms of the variables y and x, which appear in

the equation of regression (2.2), result as a consequence of the fact that time distributions are of a normal logarithmic character.

The calculation was made on the basis of a very rich statistical material consisting of 2377 pairs of the measurement results obtained by both methods in the course of experiments carried out over a period of four years. Equation (2.2) takes the form

$$\log y = 0.0318 + 0.9852 \log x \tag{2.3}$$

Applying the Student test it has been established that the two measurement methods may be considered as equivalent. The differences occurring in the measurements of time are entirely of a random character.

The correlation coefficient between $\log y$ and $\log x$ amounts to $r = 0.86$.

The registered velocities of the flame of coal dust explosions oscillated within a very wide range from about 30 to about 2000 m/sec.

Each time an explosion takes place measurements are taken simultaneously by both methods and the mean result is accepted as binding.

Yet, not infrequently, one observes differences in registration, for example, when water barriers are investigated since water delays the detonation of the lead azide.

Light-dependent resistors, the maximum spectral sensitiveness of which lies in the near infrared, are connected parallelly. In the absence of light the voltage in the light-dependent resistors attains its maximum. The lighting of any such resistors results in the lowering of the measuring voltage. The changes in the voltage are controlled by a system of hybrid amplifiers shown in Fig. 2.3. The outlet of the measuring system is connected with the galvanometer of the oscillograph. The front of the flame, moving in the direction of the outlet of the gallery, causes consecutive changes in the voltage in the photoelectric measuring systems of the separate measuring stations and these changes are registered on the moving oscillograph tape. The registration of the course of an explosion in this way provides more information that the one obtained by the detonator method since the amplitude of the record is variable. This allows to obtain data concerning the duration of the flame at each of the measuring stations which is not possible when the method of detonators is used.

2.1.3.5. Measurement of the static and the dynamic pressure. For the purpose of measuring the static and dynamic pressure in experimental galleries an 18-channel inductance pressure measuring system (type B5k) is used designed and made in the *EM Barbara*. Transducers of the static pressure are installed in the sidewalls of the gallery in steel boxes at distances representing multiples of 10. Transducers of the dynamic pressure are suspended under the roof bars in the inside diameter of the gallery's cross section, their measuring disks being turned toward the face of the gallery. These transducers are placed at selected points in the gallery.

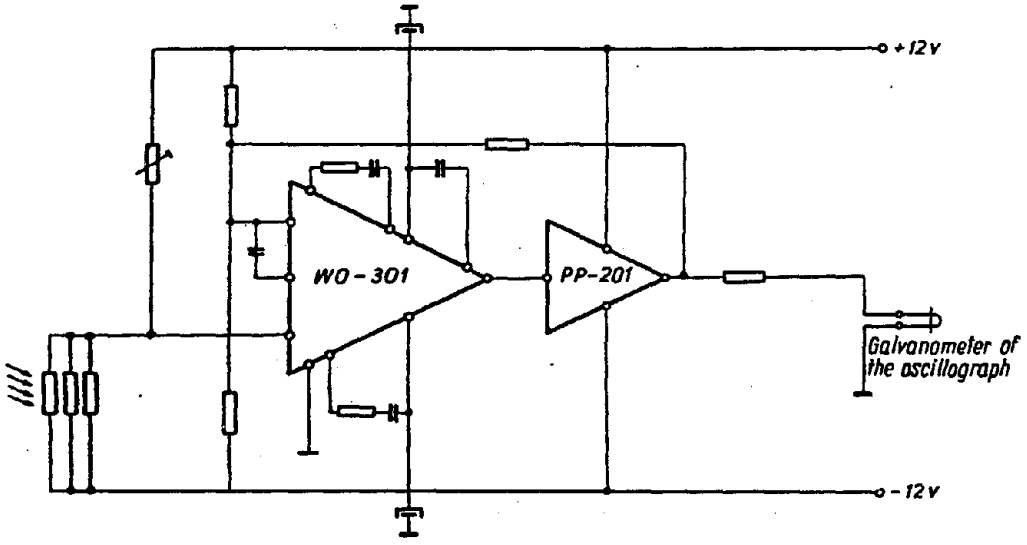


Fig. 2.3. A diagram of a single channel of the flame velocity measuring system by the photoelectric method. Denotations: *WO-301* — operation amplifier; *PP-201* — trade symbol of Polish amplifier.

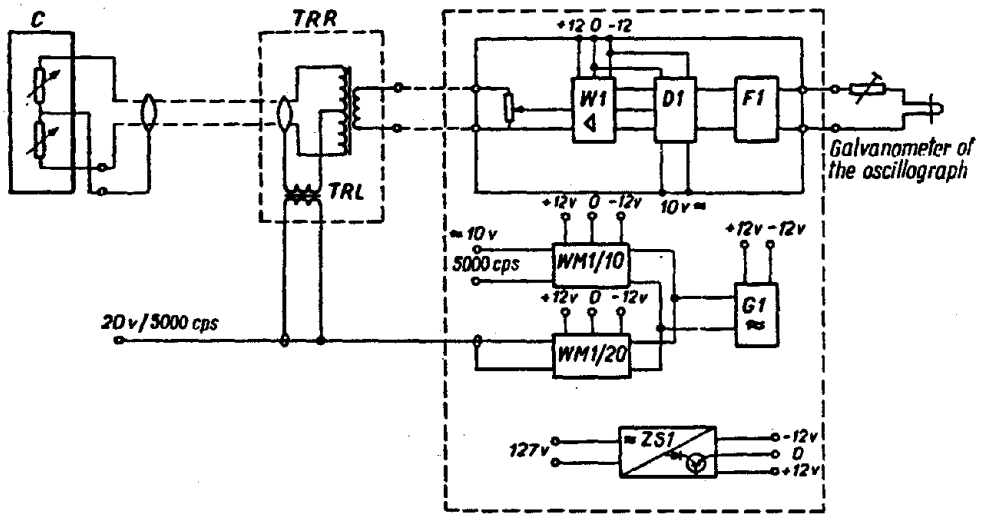


Fig. 2.4. A block diagram of the inductance pressure measuring system B5k (for a single channel) for measuring the dynamic and static pressure.

The block diagram of the inductance pressure measuring system for a single channel is shown in Fig. 2.4. The system consists of the transducer C (dynamic or static) which is a part of an a.c. bridge with a differential transformer *TRR*. This bridge is excited by a voltage of 10 v of 5000 cps. The amplifier *W1* is driven from the output of the transformer *TRR* through the measuring line. The output of the amplifier is connected with

the phase-sensitive demodulator *D1*, whose synchronizing signal is supplied by the amplifier *WM1/10*. The desired signal is transmitted by the filter *F1* to which the galvanometer of the oscillograph is connected. The bridge is excited from the amplifier *WM1/20*. Both amplifiers, *WM1/10* and *WM1/20*, are driven from the generator *G1* the frequency of which is 5000 cps. The supply voltage comes from the stabilized power supply *ZS1* connected to the underground main of 127 v.

The transducer of the static pressure shown in Fig. 2.5*a* is composed of two magnetic circuits — the active and the passive one. The active magnetic circuit consists of a diaphragm and a ferrite potcore containing a coil. This coil changes its inductance in consequence of the variation of air gap between the diaphragm and the ferrite core. The passive circuit is composed of an adjustable diaphragm and of a ferrite core containing a coil identical with the one described before. By varying the distance between the diaphragm and the core the bridge is being equilibrated. By changing the thickness of the diaphragm the maximum value of the measured pressure can be changed.

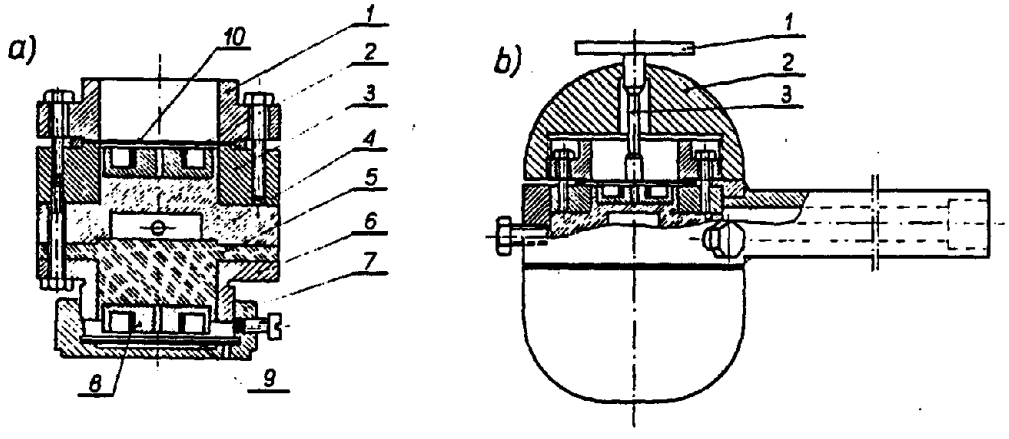


Fig. 2.5. Transducers of: *a* — static pressure (the inductance pressure system B5k): *1* — the upper case, *2* — the ferrite core, *3* — the fastening flange, *4* — the upper insulation disk, *5* — the lower insulation disk, *6* — the lower case, *7* — the regulating flange, *8* — the framework, *9* — the passive diaphragm, *10* — the active diaphragm: b — dynamic pressure: *1* — the measuring disk, *2* — the casing, *3* — the fastening mandrel.

The transducer of the dynamic pressure (Fig. 2.5*b*) differs from the transducer of the static pressure only in this that its active magnetic circuit includes a diaphragm in the center of which a rod is fixed to which a measuring disk is attached. The dynamic pressure, whose magnitude depends upon the velocity of the flow of gases, acts on the diaphragm exclusively by means of the measuring disk.

Experimental explosions are controlled from, and the resulting measurements of the explosion parameters registered at, the shotfiring and measuring center placed on the surface of the *EM Barbara*. At this center a control desk is installed as well as the measuring apparatus consisting of multichannel galvanometer oscillographs, a 16-pen chronograph and a 16-channel tape recorder. At the control desk an electric exploder is provided as well as systems signaling the state of the measuring apparatus, protection systems, a communication system (an intercome) and an interface system connecting shotfiring and measuring center arrangements into a single automatic system. In consequence of the above the act of controlling the complicated process of making ready the necessary arrangements and initiating an experimental explosion becomes simplified to a maximum degree. The course of the experiment itself is controlled entirely automatically.

The measuring apparatus is interconnected in such a way that it is possible to put into effect many combinations of connections between the particular apparatuses and, thus, to select the most suitable variant of recording the measurements.

2.1.4. General remarks on the results of investigations

The results of the tests of the course of explosions are presented in the form of graphs (Fig. 2.6). Figure 2.6*a* shows the velocity of the flame along the gallery while Fig. 2.6*b* presents the time in which the front of the flame reaches the particular points of the experimental gallery, duration of the flame at particular measuring points and both the dynamic and the static pressure. In this way a clear picture of the course of the explosion is obtained.

Figure 2.7 presents a graph of the coal dust explosion No. 558, the flame of which did not pass over the entire zone covered with coal dust. Note that when an explosion is propagated the flame of the explosion reaches markedly beyond the zone covered with coal dust since the blast which raises the clouds of coal dust carries them well beyond this zone. This is a typical phenomenon; the flame of an explosion usually goes beyond the zone in which dangerous coal dust is present — that is, coal dust capable of propagating an explosion. Since long ago investigations on the explosibility of coal dust have been carried out in the *EM Barbara* in experimental galleries, 400 and 200 m long, in the connecting gallery, as well as in the surface gallery 100 m long shown in Figs. 2.1 and 1.9. The lengths of 400 and 200 m of the experimental galleries, mentioned above, refer to the straight horizontal parts of the respective galleries and do not include their outlets.

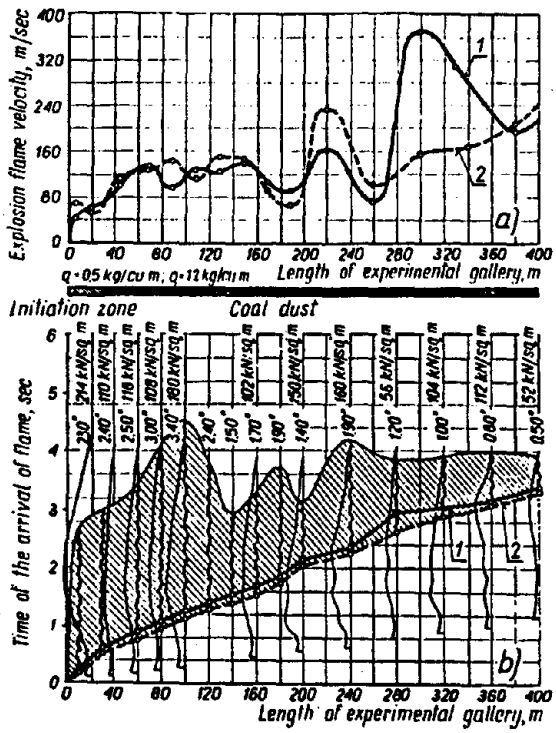


Fig. 2.6. A diagram of the propagated explosion No. 565 of the *d*85 *Barbara* coal dust; $n = 72.5\%$; $q = 1.2$ kg/cu m; the initiator used 30mPII; the easiest dispersion conditions: *a* — the velocity of the flame along the gallery; *b* — the time of the arrival of the front of the flame to particular points in the gallery; *1* — registered by the detonator method; *2* — registered by the photoelectric method.

The first initial investigation was carried out in the years 1925 and 1926 in a surface experimental gallery 44 m long. This gallery is now being used only to test explosives [29].

The number of experiments carried out in the experimental galleries and in the surface experimental gallery, the results of which are presented in this book, was very large and amounts to: 1450 made in the 400 m gallery; 4800 in the 200 m gallery; and 2850 in the 100 m gallery.

The violence of coal dust explosions varied greatly; this will be discussed later on.

It must be emphasized that special investigations on the possible most violent explosions of coal dust were not carried out in the *EM Barbara* bacause such investigations cause tremendous destructions in the experimental galleries as well as on the surface. Violently expanding upon their emergence from the outlet of the gallery the products of an explosion create a shock wave followed by a blast which might damage buildings and, in the first place, break the windows far and wide around the mine.

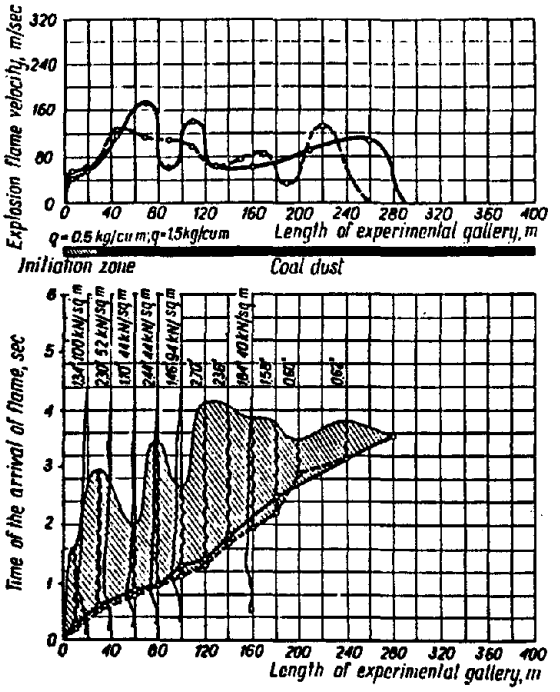


Fig. 2.7. A diagram of the nonpropagated coal dust explosion No. 558; initiator 30mPII; the *d*25 *Barbara* coal dust; $n = 65\%$; $q = 1.5$ kg/cu m; the easiest dispersion conditions.

In Fig. 2.8 a photograph is given of a very violent jet of clouds of coal dust from the outlet of the 400 m gallery. Whenever such explosions occur the flame of the explosion comes out to the surface following the clouds of coal dust and continues to develop in them on the surface.

In the course of the experiments care was taken, as far as possible, to avoid particularly violent explosions of coal dust on account of considerable damages caused by them to the steel support of galleries destined for placing coal dust on roof bars and serving as a place of measuring stations. The steel support serves also the purpose of making conditions in experimental galleries to resemble, as nearly as possible, conditions prevailing in normal mine roadways which are usually so supported. The support affects very markedly the course of an explosion since it creates a turbulent movement in the clouds of dust ahead of the flame as well as in the zone of the flame. An explosion of the same kind of coal dust in a gallery in which there is no support and where the walls are smooth develops differently.

It is worth mentioning that in order to reproduce as nearly as possible the conditions existing in mines use was made in the 200 m gallery, at the beginning of the interwar period, of a wooden support since such support

had been most common in mine roadways. This type of support, however, was very easily knocked out and, therefore, it had to be replaced by steel support. But the steel support also, in spite of a specially strong construction, suffers considerable damages when explosions are very violent. This is illustrated by Fig. 2.9 which shows a photograph of a fragment of steel support damaged by a violent explosion.

Fig. 2.8. A jet of the coal dust explosion No. 93 from the 400 m gallery.

Fig. 2.9. A photograph of the experimental gallery's support damaged by explosion No. 3574.

2.2. LABORATORY INVESTIGATIONS ON THE EXPLOSIBILITY OF COAL DUST

2.2.1. General information

For the basic laboratory investigations on the explosibility of coal dust the fineness of the coal dust used is usually below 75 μm.

The fundamental parameters are denoted as follows:

(1) the minimum explosive concentration q_{ml} — kg/cu m, or g/cu m; the symbol q_{ml} refers to laboratory investigations as distinct from the

symbol q_m which is used when investigations are carried out on a mine scale;

(2) the minimum temperature of the ignition of the dust cloud $T_{z\,min}$ — °K (°C);

(3) the minimum energy of the electric spark capable to ignite the cloud of dust E_{min} — J or mJ;

(4) the maximum pressure of the explosion P_{max} — 100 kN/sq m;

(5) the maximum velocity of the pressure rate $\left(\frac{\Delta p}{\Delta t}\right)_{max}$ — 10^2 KN/sq m sec;

(6) the minimum temperature of glow of a 5-mm layer of dust T_z — °K (°C).

The following indices which represent characteristic features of the explosibility of dusts are determined:

— index of the sensitivity of igniters

$$I_c = \frac{[q_{mt} \cdot T_{z\,min} \cdot E_{min}]_w}{[q_{mt} \cdot T_{z\,min} \cdot E_{min}]_b} \tag{2.4}$$

— index of the violence of the explosion

$$I_g = \frac{\left[P_{max} \cdot \left(\frac{\Delta p}{\Delta t}\right)_{max}\right]_b}{\left[P_{max} \cdot \left(\frac{\Delta p}{\Delta t}\right)_{max}\right]_w} \tag{2.5}$$

— index of the explosibility

$$I_w = I_c \cdot I_g \tag{2.6}$$

In the formulas (2.4), (2.5) and (2.6) the symbol w denotes the standard dust, while the symbol b — the examined coal dust.

The dust from the *Barbara* seam containing 85 percent (d85) of fraction < 75 μm is used as the standard dust. This dust has the following properties:

content of volatile matter, %	41
moisture content, %	5
ash content, %	13
temperature of the cloud ignition, °K (°C)	803,(530)
energy of the electric spark ignition, mJ	300
minimum explosive concentration, g/cu m	43.0
maximum pressure of the explosion, kN/sq m	340
maximum velocity of the increase in pressure rate, MN/sq m·sec.	5.35

Four classes of the explosibility of coal dust are distinguished as shown in Table 2.1.

Table 2.1

Classes of the Explosibility of Coal Dust in Usc in Poland and in USA

Explosibility (class)	Country	Ignition sensitivity index I_c	Explosion violence index I_g	Explosibility index I_w
Weak	Poland	< 0.1	< 0.5	< 0.05
	USA	< 0.2	< 0.5	< 0.1
Medium	Poland	0.1–1.0	0.5–1.0	0.05–1.0
	USA	0.2–1.0	0.5–1.0	0.1–1.0
Strong	Poland	1.0–2.5	1.0–2.0	1.0–5.0
	USA	1.0–5.0	1.0–2.0	1.0–10.0
Very strong	Poland	> 2.5	> 2.0	> 5.0
	USA	> 5.0	> 2.0	> 10.0

Laboratory investigations on the explosibility of coal dust were conducted in the *EM Barbara* since the time of the organization of the mine. At first these investigations comprised the elaboration of laboratory device, the so-called inflammator, which was expected to permit the determination of the explosibility of coal dust without the very expensive and labor consuming investigations carried out on the mine scale.

This device looked very much like the instrument shown in Fig. 2.10 actually used to measure the temperature of the ignition of coal dust in a cloud.

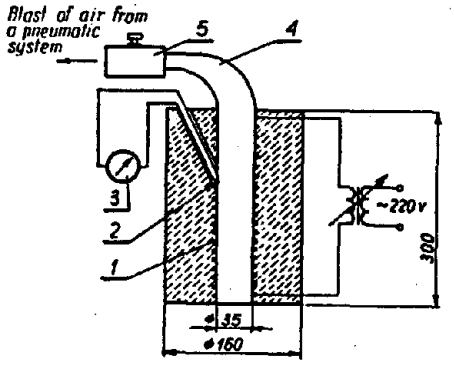


Fig. 2.10. A device for measuring the ignition temperature of a dust cloud: *1* — the resistance furnace; *2* — the thermocouple Pt-RhPt; *3* — thermometer; *4* — dispersion nozzle; *5* — a dust receptacle.

The first inflammator had been used by the often referred to French investigator Taffanel.

Efforts were made repeatedly in various countries to design an inflammator for the purpose mentioned above. In this connection British investigators Godbert and Wheeler [81] should be named.

Without going into the details of results obtained by different scientific workers it should be said that all of them proved the possible use-

fulness of the inflammator as an auxiliary device in the investigation of the explosibility of coal dust but only on a very limited scale. At any rate it has been found quite impossible to solve the basic problems of the explosibility of coal dust — as they present themselves under conditions prevailing in mines — with the aid of laboratory devices. Consequently it was necessary to expand very materially the scope of investigations on the problem of coal dust explosibility. In Poland, experimental galleries were developed in the *EM Barbara* in postwar years.

In Great Britain a very expensive new experimental gallery was recently built in which investigations can be conducted on a very large scale. In the Federal Republic of Germany, at the *Tremonia* mine, experimental galleries were also developed. In Japan, in the district of Fukuoka, a new experimental gallery was recently built.

Laboratory investigations on the basic parameters of the explosibility of coal dust are being carried out in the *EM Barbara* by J. Śliż and K. Lebecki [112].

From the experience gained it might be concluded that laboratory investigations on the explosibility of dust ought to be carried out in large, appropriately equipped, research premises. In any case, to formulate the postulate in most general terms, the investigations described above conducted under laboratory conditions ought to be at least supplemented by investigations carried out in much more capacious appropriately equipped space.

2.2.2. Investigations on the minimum ignition temperatures $T_{z\,min}$ of a coal dust cloud

In Fig. 2.10 a device is shown which serves to measure the ignition temperature of a cloud of coal dust.

When measurements are being made coal dust is used in such quantities which prove optimum for ignition. It has been found that this optimum is 7 to 10 times more than the lowest explosive concentration of a given dust. The determination of the frequency of ignition at various temperatures permits to make a statistical calculation of the limit temperature of dust ignition for the assumed probability.

Table 2.2 presents the minimum ignition temperature of coal dust clouds of typical Upper and Lower Silesian hard coals and of lignite. The minimum ignition temperature $T_{z\,min}$ in the case of hard coals was 783°K (510°C) for the coal dust from the seam 118 of the *Janina* mine with volatile matter content $V = 31.9$ percent. The minimum ignition temperature of all coal dusts, namely, $T_{z\,min} = 943$°K (670°C) was found in the

Table 2.2

Results of the Laboratory Examinations of q_{ml} and T_{zmin} of the Dust of Bituminous and Lignite Coals Depending on the Content of Volatile Matter (the fraction of the dust used had been < 75 μm; in the cases of a different fineness of the dust an appropriate indication is given in the table)

Name of mine	Seam or origin	Volatile matter V %	Ash p %	Specific surface F_w sq cm/g	Lowest explosive concentration q_{ml} g/cu m	Minimum ignition temperature $T_{z\,min}$ °K (°C)
1	2	3	4	5	6	7
Victoria	30	15.07	15.06	3830	690	943 (670)
Victoria	25	16.20	6.90	5280	95	883 (610)
Walbrzych	9	16.70	10.45	3340	700	873 (600)
Victoria	30	18.90	24.70	5750	350	943 (670)
Moszczenica	415	26.30	9.40	3600	62	813 (540)
Moszczenica	418	27.80	4.00	5650	87	803 (530)
1-Maja	626	28.06	4.10	8200	112	843 (570)
Moszczenica	505/1	28.30	2.83	4910	95	893 (620)
Moszczenica	505/1	28.60	2.80	5200	75	863 (590)
Zofiówka	407/1	28.80	14.90	4750	110	853 (580)
Victoria	25	29.70	37.70	6390	320	853 (580)
Lenin	349	30.80	17.90	4100	72	813 (540)
Halemba	405/1-H	31.10	19.07	4130	110	893 (620)
Komuna Paryska	324/1	31.50	25.55	4830	156	893 (620)
Knurów	408/1	31.80	3.40	3850	61	843 (570)
Janina	118	31.90	12.95	2240	185	783 (510)
Pstrowski	620	33.10	5.81	3300	44	803 (530)
Sosnowiec	510	33.10	9.24	3000	44	803 (530)
1-Maja	630/2	33.40	23.23	3870	56	843 (570)
Nowy Wirek	402/1	33.40	23.58	3650	87	813 (540)
Knurów	414/3	35.60	3.35	4100	88	833 (560)
Andaluzja	412	36.90	4.35	3300	31	833 (560)
Czerwona Gwardia	510	37.30	4.70	3500	45	793 (520)
Andaluzja	510	37.60	2.45	4200	37	843 (570)
Barbara	*d*25	40.50	12.40	1750	56	808 (535)
Barbara	*d*85	41.50	14.00	3850	43	803 (530)
Boże Dary	317	41.70	4.00	3900	61	863 (590)
Sieniawa	*d*25.3	54.70	8.40	1450	43	713 (440)
Sieniawa	*d*79.4	57.20	8.60	3500	31	703 (430)
Sieniawa	*d*82.4	57.20	8.60	3300	25	703 (430)
Sieniawa	*d*100	57.20	8.60	4100	25	703 (430)
Kalawsk	*d*100	59.50	17.90	18,400	62	623 (350)

case of the coal dust from the seam 30 of the *Victoria* mine with V = = 15 percent.

Lignite from the *Sieniawa* mine was found to have the minimum ignition temperature of all coal dusts $T_{z\,min}$ being equal to 703°K (430°C) with V = 57.2 percent.

On the whole the ignition temperature declines as the content of volatile matter increases which is shown in Fig. 2.11.

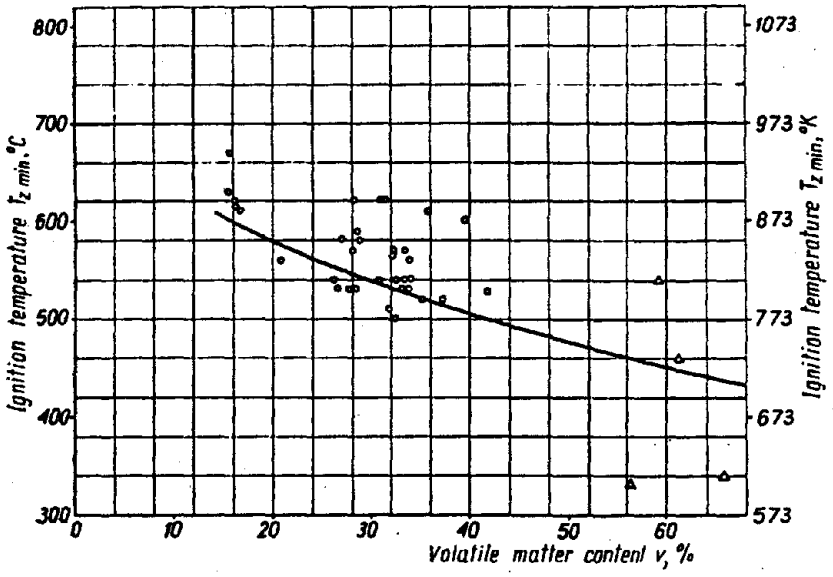


Fig. 2.11. A diagram of the dependence of the ignition temperature $T_{z\,min}$ upon the content of volatile matter V for the Upper and Lower Silesian hard coals and for lignite. The dust — fraction < 75 μm; o — hard coal; △ — lignite.

Ignition temperature of coal dust cloud depends also on the content of incombustible solid matter. This dependence is illustrated in Fig. 2.12.

2.2.3. Investigations on the minimum explosive concentrations q_{mi} of coal dust clouds

Figure 2.13 presents a device used for measuring the minimum explosive concentrations of dust.

The capacity of the container is 1.6 cu dec. As an ignition system an electric arc is employed with tungsten electrodes, the voltage being equal to 6 kv.

For every type of dust a series of tests are made with a change of the dispersion conditions for each weighed portion in order to obtain optimum dispersion of the cloud. The least weighed portion of dust, divided by the

capacity of the container at which at least one explosion occurred, determines the minimum explosive concentration. As an explosion is considered such an ignition of a dust cloud when the paper diaphragm in the container is destroyed.

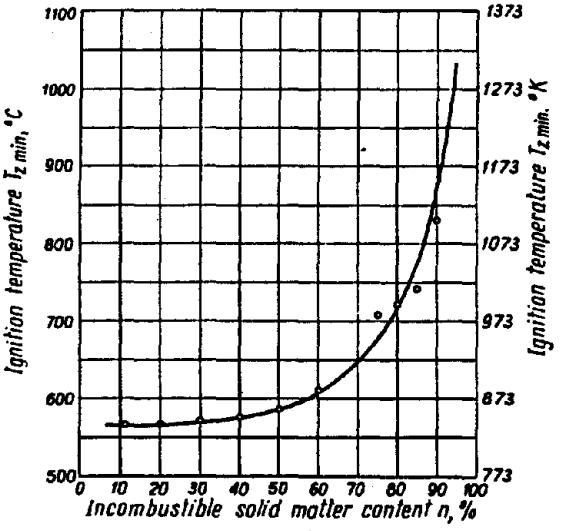


Fig. 2.12. A diagram of the dependence of the ignition temperature $T_{z\,min}$ of the *Barbara* coal dust cloud upon the content of incombustible solid matter (*n* — ordinary limestone dust).

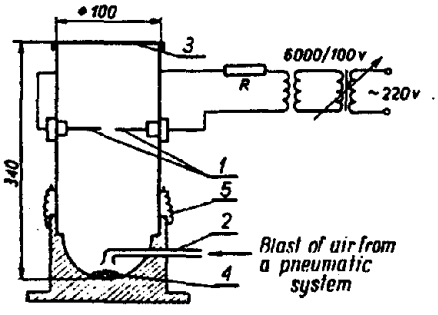


Fig. 2.13. A device for measuring the minimum explosive concentrations of dust: *1* — ignition electrodes; *2* — the dust dispersing nozzle; *3* — a paper membrane; *4* — the weighed portion of the dust; *5* — the fastening springs.

Investigations concerning the kinds of coal named in Section 2.2.2 are also presented in Table 2.2.

The content of ash *p*, as well as that of hygroscopic moisture which oscillated between 0.25 and 11.8 percent, has also had its influence on the results. The content of volatile matter *V* obviously exerts a strong influence on the minimum explosive concentration q_{mi}.

Eventually the minimum value of q_{mi} was found to be equal to 25 g/cu m for the lignite from the *Sieniawa* mine in which $V = 57.2$ per-

cent and the maximum value of q_{ml} equal to 700 g/cu m for the coal from seam 9 of the *Wałbrzych* mine where $V = 16.7$ percent.

As can be seen from Table 2.2 the scatter of the values of q_{ml} is very wide. It is noteworthy, however, that the values of q_{ml} found through laboratory tests are in many cases very close to values obtained in experiments carried out on a mine scale.

2.2.4. Investigations on the minimum energy E_{min} of the electric spark igniting a coal dust cloud

Figure 2.14 shows a device for measuring the minimum energy of an electric spark capable of igniting a cloud of coal dust. For such measurements a spark generator is used with a battery of condensers. The ignition of the dust cloud is effected by a sparkover between two tungsten electrodes the distance between which is being appropriately regulated. Perpendicularly to the two electrodes a third electrode is placed whose potential is 20 kv and which produces a weak spark for the ionization of the space between the two electrodes in order to facilitate the sparkover of the 2 kv spark.

The battery of condensers has a capacity from 0.25 to 2.0 microfarads. The high tension feed produces voltage equal to 2 kv. This voltage has a decisive influence on the result of the measurement. Actually the value of the minimum energy of a spark capable of igniting a cloud of dust — determined in this way — is obviously not an absolute magnitude and the results obtained, when the voltage of the feeder is constant, can have only a comparative worth.

The device includes a special timing system which ensures that the sparkover takes place at the moment of the optimum dispersion of the dust.

As the minimum ignition energy is regarded the maximum limit energy at which the dust cloud does not yet ignite.

The values found for E_{min} with electrode voltage equal to 2 kv were relatively high. Only in quite exceptional cases, for example, for the seam *Barbara* and the seam 510 the value of E_{min} was found to equal 200 mJ. In some tests the value of E_{min} was even more than 3000 mJ.

American investigators [126] found the value of E_{min} to be about 50 mJ for American coals with volatile matter content very nearly the same as that of Upper Silesian coals but the voltage of the electrodes was 40 kv.

The value of E_{min} depends on the concentration of oxygen in the air. For coals in which the content of volatile matter was high it was found [92] to be impossible to ignite a cloud of dust by an electric spark when

the content of oxygen in the air had been 15 to 17 percent. For coals of medium volatile matter content the corresponding limit concentration of oxygen was 18 percent.

2.2.5. Investigations on the maximum pressures of coal dust explosions P_{max} and the pressure rate $\frac{\Delta p}{\Delta t}$

A device for measuring the pressures of coal dust explosions and the pressure rate is shown in Fig. 2.15.

The pressure rate of the explosion is the measure of the velocity of the reaction of the explosion. The way in which the cloud of dust is ignited is the same as in the case of determining the minimum explosive concentration of the dust.

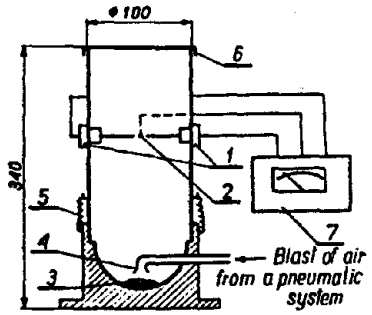


Fig. 2.14.

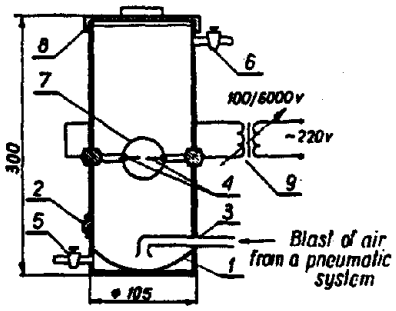


Fig. 2.15.

Fig. 2.14. A device for measuring the minimum energies of the electric spark igniting a dust cloud: *1* — ignition electrodes; *2* — starting electrode; *3* — the weighed portion of the dust; *4* — the dust dispersing nozzle; *5* — the fastening springs; *6* — the perforated cover; *7* — the measuring appliance and the condenser battery.

Fig. 2. 15. A device for measuring the pressures of dust explosions and the pressure rate: *1* — a bowl into which the dust is poured; *2* — the opening through which the dust is poured; *3* — the dust dispersing nozzle; *4* — ignition electrodes; *5* and *6* — the taps for filling the container and for drawing gas samples; *7* — the pressure transducer; *8* — the cover; *9* — the starting transformer.

The single-coil induction pressure transducer is placed opposite the electrodes. The course of the pressure is recorded by an oscillograph. The oscillograph chart of the course of pressure (Fig. 2.16) makes it possible also to determine the pressure rate.

The pressures caused by explosions depend, naturally, on the concentration of dust in the cloud; therefore, measurements are taken for various concentrations in the clouds in order to find the maximum value of the explosion pressure and of the pressure rate.

The resulting denotations of P_{max} for dusts from different coal seams

showed a very wide scatter. The highest value found for P_{max} was 500 kN/sq m.

American investigators [126] found $P_{max} = 700$ kN/sq m which is a value corresponding to that given by Bartknecht [7].

The maximum pressure rate $\frac{\Delta p}{\Delta t}$ that was found in the EM *Barbara* had been 5.35 MN/sq m·sec for the dust from the seam *Barbara*.

American investigators [126] came to very similar results in determining the value for $\frac{\Delta p}{\Delta t}$.

Note that the shape of devices described here, with the exception of the one shown in Fig. 2.10, should be rather more spherical. Their capacity should also be higher.

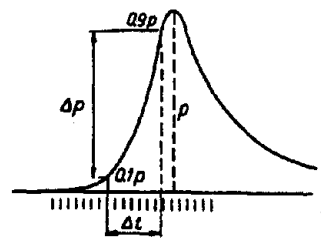


Fig. 2.16. Oscillograph chart of a coal dust explosion pressure recorded by the device shown in Fig. 2.15.

According to Bartknecht [7]

$$\left(\frac{dp}{dt}\right)_{m1} \cdot V_1^{\frac{1}{3}} = \left(\frac{dp}{dt}\right)_{m2} \cdot V_2^{\frac{1}{3}} = \text{constant} \qquad (2.7)$$

where

$\left(\frac{dp}{dt}\right)_{m1,m2}$ — the appropriate differential pressure rate,

V_1, V_2 — the capacity of the measuring devices.

According to the same author the minimum pressure of a coal dust explosion in closed containers comes to approximately 700 kN/sq m.

The glow temperature of the dust is determined by placing a 5-mm layer of the dust on the surface of a heating plate.

The devices and measuring methods described above are employed also when other explosive dusts are investigated.

2.2.6. Examples of the explosibility indices of coal dusts

On the basis of the results of investigations discussed in Sections 2.2.2 and 2.2.5 it is possible to calculate explosibility indices I_c, I_g and I_w.

Table 2.3 contains examples of the explosibility indices calculated for

Table 2.3

Examples of the Explosibility Classes of Coal Dust Ascertained through Laboratory Tests

Mine, seam	Volatile matter V, %	Ignition sensitivity index I_c	Explosion violence index I_g	Explosibility index I_w	Explosibility (the class of)
Moszczenica 505 *d*85	28.6	0.083	0.33	0.03	weak
Barbara 310 *d*85	41.2	1	1	1	medium
Barbara 310 *d*25	41.2	0.2	0.63	0.12	medium
Andaluzja 412 *d*85	36.8	0.58	1.88	1.07	strong

coal dusts from several seams. The *d*85 dust from the *Barbara* seam had been adopted as the standard dust (*d*85 denotes the content of 85 percent of fraction < 75 μm). The explosibility indices given in Table 2.3 do not agree at all with the results of investigations conducted on a large scale. Of course the latter are the more dependable ones.

Actually the explosibility of coal dusts of a similar degree of fineness with volatile matter content in excess of 25 percent shows very small differences as evidenced by the basic investigation in the *EM Barbara* to be discussed later on.

It is to be expected that — when investigations on the minimum energy sufficient for the ignition of a cloud of coal dust shall be carried out more extensively — the indices of the explosibility of coal dust determined in laboratories would possess a higher practical value.

It can be said, for the purpose of comparing the explosion violence index I_g for typical Polish coals with the analogous index for similar American coals (Table 2.1), that the value of I_g for the latter oscillates between 0.7 and 1.5, while for coals with volatile matter content slightly below 25 percent this index is 0.2.

2.2.7. Limit concentrations of oxygen in the air below which the ignition of a coal dust cloud becomes impossible

Under conditions prevailing in mines the content of oxygen in the

air is often reduced and, therefore, the influence of this phenomenon upon the ignitability of coal dust is of considerable practical importance.

American investigators [92] had carried out laboratory tests on the influence of oxygen content in the air upon the possibility of igniting coal dust by an electric spark and in a pipe furnace (inflammator). These tests were made for typical coals.

The dust from coals containing 16 percent of volatile matter could not be ignited by an electric spark. For coals containing about 24.7 percent of volatile matter the limit content of oxygen, at which the ignition by an electric spark was possible, amounted to 18.5 percent while for coals in which the contents of volatile matter were between 34.8 and 40 percent this limit oxygen content oscillated between 15 and 17 percent.

For all these coals the limit oxygen content found in the inflammator amounted to 10.5 percent.

In his so far unpublished investigations Rae, using a "rocket" initiator, found for typical British coals limit oxygen concentrations to be 17.5 percent at the temperature of 293°K (20°C) and 16 percent at the temperature of 343°K (70°C). In these tests the decrement of oxygen had been replaced by carbon dioxide. When the oxygen decrement had been replaced by nitrogen the corresponding limit oxygen contents were found to amount to 15.8 percent at the temperature of 293°K (20°C) and 14.5 percent at the temperature of 343°K (70°C).

These tests proved that carbon dioxide is more effective than nitrogen in hampering the ignition of coal dust.

It may be assumed, in respect of the average Upper Silesian coals, that coal dust is incapable of propagating explosions when the oxygen content in the air is below 16.5 percent. This figure is fixed for air containing no methane.

Note that all the results of investigations, concerning the explosibility of coal dust given in the following sections, refer to the normal composition of the air. In coal mines, particularly in exhaust air currents, oxygen concentration is reduced; according to regulations it may amount to 19 percent. This gives a certain margin of safety in relation to the limit values of the explosibility of coal dust.

2.2.8. Comparison between the explosibility of coal dust and that of other industrial dusts

While coal dust is a source of great danger in mines there are, nevertheless, many industrial dusts whose explosibility is considerably higher than that of coal dust. If coal dust had been responsible for much more

Table 2.4

Results of Laboratory Tests of the Explosibility of Industrial Dusts [98] and [126] (All Data Pertains to Dust Clouds)

Kind of dust	Lowest explosive concentration q_{mt} g/cu m	Minimum temperature of the ignition of the dust cloud $T_{z\,min}$ °C	Minimum ignition energy mJ	Maximum explosion pressure P 100 kN/sq m	Maximum pressure rate of explosion $\frac{\Delta p}{\Delta t}$ 100 kN/sq m · sec²
1	2	3	4	5	6
Starch of cereals	40	380	20	8.05	630
Rubber (caoutchouc)	30	360	30	5.6	197
Nylon (polymer)	30	500	20	7.3	280
Polyethylene	20	450	30	6.7	238
Polyvinyl chloride		680		1.2	14
Aluminum	45	650	50	5.1	1400
Magnesium	40	620	40	6.3	630
Zirconium	45	20	15	3.8	455
Zinc	500	680	960	3.3	126
Hard coal (*Barbara*, *d*85)	43	530	300	3.4	53.5
Lignite (the *Kalawsk* mine, *d*100)	62	350	100	6.0	160

serious disasters than other, more explosive, industrial dusts it was due to the fact that coal dust is present in mines in very large quantities over long roadways in the workings.

In the industrial plants located on the surface the accumulation of dangerous dusts is considerably smaller and usually localized. It facilitates greatly the combating of the danger of their explosion and restricts the range of their impact.

As examples of particularly explosive dust the dusts of magnesium, zirconium and titanium should be named which explode even in the atmosphere of carbon dioxide.

In the course of the explosion reactions these metals take oxygen away from carbon dioxide.

Table 2.4 presents results of laboratory tests on the explosibility of many industrial dusts [98], [126].

The same table contains parameters of the explosibility of the typical Upper Silesian coal dust used in very many investigations and those of lignite dust.

As can be seen from Table 2.4 hard coal dust differs markedly from many industrial dusts in its minimum energy of ignition which is considerably higher for coal than that of most industrial dusts. The value $\frac{\Delta p}{\Delta t}$ on the other hand is much lower than that for almost all industrial dusts.

The minimum ignition energy of lignite dust is lower than that of hard coal. The value $\frac{\Delta p}{\Delta t}$ for lignite, however, is very close to that for several industrial dusts.

2.3. THE THEORY OF COAL DUST EXPLOSIONS

The theory of coal dust explosions can be divided into three parts pertaining to the problems of:

— the ignition of coal dust,

— the propagation of a coal dust explosion — that is, its development,

— the basic phenomenon occurring in coal dust explosions in mine workings or in experimental galleries.

The problem of coal dust explosions is much more complicated than that of the explosions of gases. Actually while the theory of explosions of gases, particularly of their detonation, is very far advanced the same cannot be claimed for the theory of coal dust explosions. The works carried out thus far on that problem have not yet been summed up nor generalized though the accomplishment of these tasks is so much desired by research workers.

2.3.1. Ignition of a coal dust cloud

All investigators agree that the evolution and combustion of volatile matter plays the basic role in the phenomenon of the coal dust explosion.

Volatile matter burns away earlier — that is, before the greater part of solid coal can take share in the combustion. Already Taffanel [167] had considered this problem. For the phenomenon to develop in this way it is obviously necessary that the velocity of the evolution of volatile matter should be very high which is possible only if the grains of coal are heated at a very high rate by heat radiation.

Long and Murray [114] contributed very valuable theoretical considerations on the pre-reaction zone in the coal dust cloud. In the opinion of these investigators the radiation effects can appear at very long distances from the flame front depending on the absorption capacity of the dust cloud. This results in a more gradual increase in temperature than in the case of the heat transfer by conductivity alone. The effect of conductivity might appear at distances of the order of several hundred micrometers from the flame front.

It is known that the lengths of the light waves in the radiation of a flame oscillate between 0.9 and a dozen or more micrometers; in other words between near ultraviolet and far infrared. The radiation is a feature inherent in a coal dust explosion, hence the conception of using detectors with triggered barriers whose action is based on the detection of the explosion radiation. The radiation of the flame front is strongly absorbed by the raised cloud of dust. The quantity of the energy absorbed by a dust cloud is proportional to the 4th power of the flame temperature (estimated according to the kinetics of chemical reactions as equal to 2300°K) and it depends, in a high degree, upon the concentration of the dust cloud and upon the fineness of the dust grains. Introduction of large quantities of an inert stone dust to the flame front makes possible the radiation to be considerably reduced which restrains any increase in the temperature of further dust layers. The role of water in barriers is, in a certain measure, similar to the role of stone dust since finely sprayed water strongly absorbs infrared radiation. The absorption is slightly lower than that for stone dust but water absorbs great quantities of energy for evaporation.

An American investigator [172] (Table 2.5) expressed, in a very interesting and simple manner, the relative velocities of the three types of chemical processes of explosions and the mechanism of the heat transfer. Flame velocities are determined qualitatively.

In connection with Table 2.5 an idea suggests itself that a more precise definition of the thermal initiation can also cover the role of radicals.

A mixture of volatile matter with air is explosive and very easily in-

flammable. Therefore, the simplest explanation of the ignition of coal dust is exactly the possibility of a rapid evolution of volatile matter and its ignition in the mixture with air. This explanation seems to be, at least at the first glance, the most probable.

Table 2.5

Types of Explosions Connected with a Chemical Reaction

Name of the process	Velocity	Mechanism of the heat transfer
Thermic	very slow	conductivity convention
Deflagration	from low to high	conductivity convention radiation
Detonation	very high (> 1000 m/sec)	hydrodynamic

Very interesting and fundamental investigations on the mechanism of the ignition of coal dust were carried out by Loison and Chauvin [113]. They questioned the opinion that volatile matter plays the role of the factor which initiates the coal dust explosions. The course of the phenomena leading to the ignition of coal dust is conditioned primarily by two phenomena: the oxidation and pyrolysis depending on temperature. The above named investigators carried out their experiments with a rapid heating of the dust of seven kinds of coals containing from 10.2 to 38.9 percent of volatile matter. They subjected the pyrolysis products to an examination and came to the conclusion that tar yield plays a peculiar role in the process. This yield is very high in the case of fat and flame coals. It does not, however, increase steadily with the increase of the volatile matter content. It reaches a certain maximum which is exactly in accord with the results of the explosibility investigations. Though the composition of the tar obtained under conditions of experiments is not yet very well identified it is established, at any rate, that it consists of products of great molecules and their ignition temperature is relatively very low — about 600°K (300°C).

2.3.2. Propagation of a coal dust explosion

2.3.2.1. An attempt undertaken by French investigators to explain the propagation of coal dust explosions. Loison and Chauvin [113] worked also on the problem of the propagation of coal dust explosions.

As is known the lowest explosibility limit of hydrocarbons requires the fulfilment of an empirical condition consisting in this that the heat of

the combustion of 1 cu m of their mixture with air should not be lower than 550 kcal/cu m.

Taking into account that the heat of the combustion of tar H = = 10,000 kcal/kg the lower limit explosibility of tar would have amounted to 55 g/cu m.

For coals yielding 25 percent of tar this would correspond to the lower limit explosibility of coal dust equal to 220 g/cu m. But according to results obtained in the *EM Barbara* the lowest limit explosibility of similar coal dust amounts to about 50 g/cu m. This proves that the propagation of a coal dust explosion can be caused without satisfying the condition of the distillation of the volatile matter in a quantity sufficient to make the gaseous mixture explosive.

Of course, the above mentioned caloric condition might be fulfilled by concentrating coal dust far beyond the lowest limit concentration. Loison and Chauvin supposed that during an explosion there is a zone in the cross section of the gallery where the coal dust concentration is much higher than the one expected on the assumption that there is an equal dispersion of coal dust in the cross section of the gallery. Undoubtedly — coal dust is dispersed unevenly in its clouds. However in the previously mentioned Polish investigations on the minimum coal dust concentrations, sufficient to propagate explosions, coal dust had been distributed with particular care so that its dispersion in the cross section of the gallery would be as equal as possible; moreover, with this end in view, a very powerful initiator of firedamp explosion was used.

Consequently, it cannot be admitted that the above described attempt to explain the energetic discrepancy in question has been successful.

2.3.2.2. Examining the residue after coal dust explosions in the experimental gallery. After coal dust explosions it is possible to find left in mine workings, as well as in experimental galleries, grains of coke or even whole agglomerations of coke in cases when the coal was of the coking type. Since long ago, on the basis of these observations, in the *EM Barbara* steps were taken after explosions in mines to determine whether coal dust participated in a given explosion or not. This method helped also in determining the range of explosions if conditions of workings permitted it.

An exact determination of the coke grain content in the dust, remained in an experimental gallery after an explosion, has its importance also in the research on the essentials of a coal dust explosion or, to express this more precisely, in the explanation of the propagation mechanism of a coal dust explosion.

In the *EM Barbara*, in the course of many years, works were carried

out to quantitatively determine the coke grain content in the dust left after 323 explosions in the experimental gallery of 200 m in length.

When an explosion is propagated over the entire zone 200 m in length, under the easiest dispersion conditions, about 25 percent of coal dust is ejected from the experimental gallery to the surface. During these investigations were also determined: the volume of volatile matter evolved during coal dust explosion and the loss of free water when experiments were carried out with wet coal dust. These investigations consumed a lot of labor since coal from 18 seams was examined. The greatest number of tests, however, was made with coal dust from the seam *Barbara*. That these investigations were immensely labor consuming is testified by the fact that percentages of coke grain contents were determined for 4385 samples and that 1460 dust samples were taken for detailed analyses. This work is not yet published by the present author on account of its rather wide scope but the most essential results are being included in the present publication.

The following explosion initiators were used: 50 cu m CH_4, 30mPII and the direct initiator — that is, shotfiring of 750 g of gunpowder. A fine (*d*85) and medium (*d*25) coal dust was used in the experiments.

The coal dust used was either pure — that is, with natural content of incombustible matter or mixed with limestone dust.

After each explosion many samples were taken from the entire length of the 200 m gallery. Yet the greatest weight was attached to the average samples taken from the whole coal dust remaining after the explosion.

Content of coke grains was determined separately for three fractions of dust, namely:

I	from	385	to	100	μm
II	„	120	„	385	„
III	„	75	„	120	„

The average results of a part of investigations made are scheduled in Table 2.6. They have a basic significance and a practical importance. Of particular interest are results obtained after explosions of minimum pure coal dust concentrations which, however, were sufficient to propagate an explosion. As it can be seen from Table 2.6 for the pure *d*85 *Barbara* coal dust with a concentration approaching the lower limit concentration $q = 76$ g/cu m and the initiation with 50 cu m CH_4 9.5 percent, the average content of coke grains after the explosion amounted to: $\bar{x} = 22$ percent. For d25 coal dust with $q = 135$ g/cu m, under quite analogous conditions, the value of $\bar{x}$ was found to equal 55 percent. For the same *d*25 dust, when direct initiator was used, the value of $\bar{x}$ amounted to 21 percent. Note, however, that in this last mentioned case the concentration of the dust had

Table 2.6

Results of the Examination of Coal Dust after Its Explosions in the 200 m Experimental Gallery
(the schedule contains the mean results of a part of examinations)

Type of coal dust			Initiator	Volatile matter content		Fineness after explosion (the mean value)	Free water content (the mean value)		Content of coke grains K, %		
d	n	q		before explosion L_0	after explosion L	d	before explosion	after explosion	mean of the bulk	maximum of the samples	mean of the samples
%	%	g/cu m		%	%	%	%	%	$\bar{x}$		
Dry coal dust, the *Barbara* mine, the *Barbara* seam											
						pure dust					
85	14.7	76	50 cu m CH_4	—	—	57.6	—	—	22.0	44.0	16.2
25	12.8	135	50 cu m CH_4	41.1	36.2	38.7	—	—	55.0	98.5	39.6
25	12.8	261	direct	40.5	31.4	27.1	—	—	21.0	34.0	13.2
						mixed dust					
86	70.8	486	50 cu m CH_4	—	—	60.6	—	—	17.3	73.0	31.4
85	80.0	750	30mPII	—	—	59.5	—	—	30.0	72.5	22.1
Wet coal dust, the *Barbara* mine, the *Barbara* seam											
						pure dust					
85	14.7	500	50 cu m CH_4	41.6	27.0	79.7*	34.2	5.7	—	34.0	6.8
25	13.9	1125	30mPII	41.0	30.3	41.2*	25.1	11.3	—	39.0	6.1
						mixed dust					
25	30.0	2000	50 cu m CH_4	42.5	40.0	22.7	11.7	8.2	5.1	8.9	4.3

Dry coal dust, the *Gliwice* mine, seam No. 123												
						mixed dust						
85	72.5	600	50 cu m CH_4	32.0	17.3	81.5	—	—	34.5	87.0	46.2
Dry coal dust, the *Gliwice* mine, seam No. 152												
						mixed dust						
25	65.0	950	50 cu m CH_4	34.4	29.6	48.1	—	—	32.4	36.0	19.7
Dry coal dust, the *Marcel* mine, seam No. 708												
						mixed dust						
85	60.0	800	30mPII	41.6	29.8	83.4	—	—	71.5	—	—
Dry coal dust, the *Mieszko* mine, seam No. 25/29; flat I												
						mixed dust						
85	46.0	750	50 cu m CH_4	15.3	11.5	74.2	—	—	40.0	97.1	38.5
85	58.7	750	30mPII	15.5	14.5	76.0	—	—	78.3	97.0	68.4
25	30.0	1000	50 cu m CH_4	16.5	10.7	44.5	—	—	85.8	94.8	83.4
25	38.5	750	30mPII	15.1	10.9	45.5	—	—	55.7	96.6	51.6
Dry coal dust, the *Mszana* mine, seam No. 11												
						mixed dust						
25	60.0	900	50 cu m CH_4	37.4	29.4	59.9	—	—	18.0	—	—
25	65.0	900	30mPII	37.1	31.6	59.5	—	—	32.2	—	—
Dry coal dust of lignite, the *Sieniawa* mine												
						mixed dust						
85	75.8	500	50 cu m CH_4	66.8	48.0	55.7	—	—	16.9	25.0	8.6
25	67.5	625	30mPII	60.3	46.1	49.2	—	—	5.4	12.5	4.6

*The mean value of the separate samples (not of the bulk).

been twice as high as in the case in which the initiator used was 50 cu m CH_4 9.5 percent. The result, therefore, has a sound explanation.

It is also very interesting that d85 coal dust containing incombustible solid matter $n = 70.8$ percent produced after an explosion $\bar{x} = 17.3$ percent with $q = 468$ g/cu m. This result is likewise quite logical and confirms that for the propagation of the explosion considerably more coal dust grains per unit of volume must have participated in the chemical reaction than would have been the case if pure coal dust was used.

After an explosion a comparison was made between the contents of coke grains in the particular fractions of dust. Statistical analysis indicated that there is an essential difference between the average values of $\bar{x}$ for fractions I and II. Fraction I, consisting of larger grains, contains clearly less coke grains than fraction II. On the other hand no essential difference has been found between the contents of coke grains in fractions II and III.

These results differ from the results of laboratory tests conducted by Brookes [11] which demonstrated that particles of coal up to and above 150 μm, subjected to a heat radiation with a constant intensity, show an almost immediate ignition of volatile matter; the coking residue burns some time later. In cases in which coal particles smaller than 500 μm are subjected to a gradually (though rapidly) increasing radiation volatile matter was not ignited.

The above divergence of results emphasizes the complexity of the phenomenon and shows the difference between laboratory and mining conditions.

Considerable importance has been attached to the investigation of the loss of volatile matter in the dust after an explosion. The most dependable results were obtained in the cases in which pure coal dust was used.

For the d25 *Barbara* dust the decrease in the content of volatile matter was found to be 4.9 percent when the initiator used was 50 cu m CH_4 9.5 percent, and 9.1 percent when direct initiator was used.

In general it was established that the loss of volatile matter does not appear to correspond to the role which is ascribed to this factor in the question of the explosibility of coal dust. Note that data given here pertains to coal dust concentrations approaching the lowest limit concentrations.

Tests were also made of the fineness of the dust remaining after explosions.

Assuming that the finest fractions of coal dust have the greatest participation in the combustion reactions it should be expected that the value of d in the dust after an explosion would decline.

Fig. 2.17. Coke grains of the fraction 0.4 to 1 mm after a coal dust explosion as seen through a microscope: *a* — in experimental gallery; *b*, *c* — in active colliery.

Actually when the *d*85 coal dust was examined it was ascertained that the value of *d* decreased by about 27 percent.

However, in the case of *d*25 coal dust the value of *d* increased by about 14 percent or no difference was registered.

The inconsistency of these results is difficult to explain. Note, however, that fractions of *d*85 dust might contain fine coke.

Table 2.6 includes also interesting data concerning the decrease in the free water content after explosions of wet coal dust.

Though the experiments, discussed above, produced a number of interesting information attention should be paid to the following fact which, in a certain measure, lowers their value. The physicochemical properties of coal dust after an explosion are affected by the time during which the flame persists in the experimental gallery. This time is longer

than the duration of the flame in the reaction zone which decisively determines the course of the explosion. In consequence of this, further changes occur in the coal dust and in examining the dust after the explosion one does not get an accurate picture of the changes which played the essential role in the development of the explosion.

Figure 2.17 presents coke grains after an explosion in an experimental gallery, and after an explosion in the active colliery. Naturally, they do not show any difference.

2.3.2.3. A thermochemical explanation of the propagation of coal dust explosions. In the course of investigations included in Table 2.6 a propagation of an explosion of the d85 coal dust had been obtained at a concetration $q = 76$ g/cu m. The course of this explosion is graphically represented in Fig. 2.18. However, it is also possible to obtain a propagation of the explosion of the same dust at a concentration $q = 50$ g/cu m. This is a limit value and the propagation does not occur every time.

Considerations presented in this section are illustrated by results obtained through the explosion of dust with $q = 76$ g/cu m since the results in question were available.

Assuming a total evolution of volatile matter from the coal dust during an explosion the quantity of heat emitted, as a result of the combustion of the volatile matter, would be

$$Q_{L\,compl} = 144.1 \text{ kcal/cu m}$$

This quantity is absolutely insufficient for the development of an explosion in a mixture of hydrocarbons with air. The minimum heat of combustion required for this purpose is 550 kcal/cu m.

Assuming the total combustion of 76 g of coal the quantity of heat emitted would be

$$Q_{C\,compl} = 516.8 \text{ kcal/cu m}$$

Actually, of course, neither the volatile matter evolved completely, nor the entire quantity of dust was burnt.

On the basis of data presented in the preceding section it was found that the quantity of heat emitted from the combustion of volatile matter really evolved was

$$Q_{Lr} = 48.7 \text{ kcal/cu m}$$

During the explosion a certain part of the finest coal dust fractions was completely burnt. On the basis of investigations made it is possible to assume that this part of coal dust does not exceed 20 percent of its total quantity. This would correspond to the quantity of the heat emitted

$$Q_{Cr} = 103.4 \text{ kcal/cu m}$$

If the phenomenon of the explosion occur under conditions of the normal pressure the total quantity of heat emitted would be

$$Q_{Lr} + Q_{Cr} = 152.1 \text{ kcal/cu m}$$

Pressures which do occur during coal dust explosions are always both static and dynamic. In consequence of this fact the zone in which the explosion reaction takes place shows a density of gas higher than that of the air beyond the reach of the blast of the explosion. Obviously, therefore, the concentration of coal dust in the zone of its explosion is always higher than the concentration which would occur should the coal dust be simply raised to the air and become evenly dispersed in it.

To be precise note that in determining the minimum concentration of coal dust, capable to propagate an explosion, the quantity of coal dust

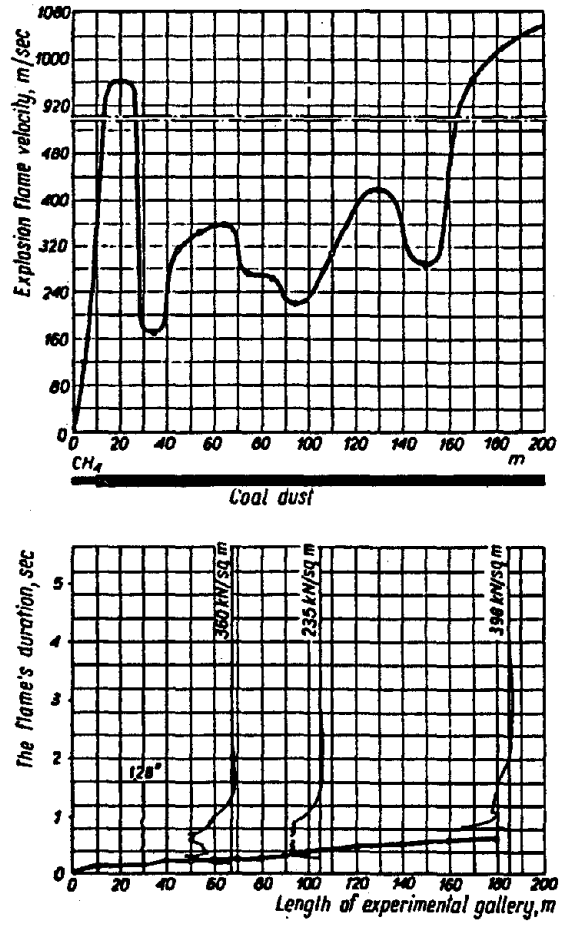


Fig. 2.18. A diagram of explosion No. 2249 of the d85 *Barbara* pure coal dust; initiator 50 cu m CH_4; q = 76 g/cu m.

deposited in the mine working, expressed in terms of its ratio to the volume of the working, is simply accepted as this value. The minimum coal dust concentration capable of propagating an explosion so expressed obviously does not represent the real concentration of coal dust in the zone of the explosion. This concentration can be calculated approximately if the static pressure, prevailing in the zone of the explosion, is known. Of course, it should be assumed that the entire coal dust present in the roadway had been raised to the air and uniformly dispersed in it.

Pressure plays the principal role in the explosion of coal dust, and that both at its initiation and its development. The well known British investigator Rae even suggested that coal dust might be incapable of exploding under the normal atmospheric pressure. At any rate considerations presented in this section confirm the above mentioned opinions concerning the great role of pressure in the process of coal dust explosion.

In the *EM Barbara* in the course of many years of investigating various coal dust explosions static pressure registered oscillated from 10 to 1200 kN/sq m. In some cases the pressure exceeded the measuring range of the instruments used.

For the consideration of involved problems, from the point of view of energetics, the most interesting are both: the minimum pressure at which an explosion can develop, and the maximum pressure that can be taken into account. For any static pressure assumed it is possible to calculate the magnitude of the heat energy produced per unit of volume in the zone of the explosion.

In the now considered example of an explosion, presented in Fig. 2.18, the static pressure recorded during the explosion has to be taken into account. The value of the static pressure varied throughout the path of the explosion; as the basis for calculations the pressure registered approximately in the middle of this path — that is, at the distance of 105 m from the face, was taken; it amounted to 230 kN/sq m.

Taking into account an appropriate increase in the coal dust concentration in the explosion zone it is found that the quantity of the heat energy, emitted as a result of the combustion of 22 percent of the entire volatile matter and of the complete combustion of 20 percent of dust, amounted to

$$Q_P = 349.8 \text{ kcal/cu m}$$

During the explosion a great role is played by the shock wave which moves ahead of the flame front and causes an increase in the temperature of the gaseous medium (the air). In consequence, the gaseous medium receives from the shock wave large quantities of heat.

The temperature increment after the passing of the shock wave de-

pends upon its velocity. The velocity of the shock wave depends upon the flame velocity.

The values of the above mentioned parameters are listed in Table 2.7 and give a picture of the dependence of the shock wave velocity upon the flame velocity, and also the effect of the shock wave velocity on the increase of the temperature and, consequently, on the amount of heat imparted to the gaseous medium.

As can be seen from Table 2.7 with the increase in the flame velocity W and, consequently, with the increase in the shock wave velocity U_d increments in the temperature ΔT as well as in the quantities of the heat energy Q imparted to the gaseous medium grow very materially.

In the case of $W = 2000$ m/sec, $U_d = 2000$ m/sec the so-called paradetonation occurs for which increments of the temperature of the gaseous medium $\Delta T = 1465$ deg, $\varrho_1 = 12.3$ kg/cu m, $Q = 212 \cdot 10^5$ J/kg.

It can be seen from Fig. 2.18 that the velocity of the flame in the now discussed explosion of the d85 coal dust, when $q = 76$ g/cu m, varied but exhibited a distinct acceleration.

When the assumed flame velocity $W = 400$ m/sec, the velocity of the shock wave $U_d \approx 600$ m/sec, $\Delta T = 170$ deg.

The quantity of heat imparted to the gaseous medium amounts to

$$Q_{W\,400} = 121 \text{ kcal/cu m}$$

As the result the total quantity of the heat released in the explosion in question amounted to

$$Q_s = Q_p + Q_{W\,400} = 470.8 \text{ kcal/cu m}$$

With the assumed flame velocity $W = 600$ m/sec the quantity of the heat emitted in the explosion would have been

$$Q_s = 601.8 \text{ kcal/cu m}$$

The values of Q_s found in this way are somewhat overestimated.

The flame life of a coal dust explosion is long in general. In many cases of explosions it can be observed that, when the front of the flame approaches the end of the investigated zone of the experimental gallery, the flame still persists at the face of the gallery. The flame life varies but, in general, it is longer than the duration of the explosive reaction which has a decisive influence on the course of the explosion.

The zone of the reaction which determines the course of an explosion may be called the reaction zone of the explosion. In the end the particles of coal dust are subjected to a further impact of high temperature beyond the reaction zone of the explosion. As the effect of this prolonged influence of high temperature on coal dust the percentage of coked grains of coal

Table 2.7

The Basic Thermodynamic Data for Strong Coal Dust Explosions

Flame velocity W, m/sec	Shock wave velocity U_d, m/sec	Temperature T, °K	Medium density behind shock wave ρ, kg/cu m	Heat imparted to 1 cu m of air	
				Q, J/kg	Q_1, cal/kg
260	500	90.6	2.22	$2.10 \cdot 10^8$	$0.550 \cdot 10^5$
333	550	140	2.53	$3.72 \cdot 10^8$	$0.575 \cdot 10^5$
401	600	171	2.82	$5.05 \cdot 10^8$	$1.21 \cdot 10^5$
465	650	204	3.10	$6.65 \cdot 10^8$	$1.59 \cdot 10^5$
528	700	240	3.37	$8.50 \cdot 10^8$	$2.04 \cdot 10^5$
590	750	277	3.62	$10.52 \cdot 10^8$	$2.52 \cdot 10^5$
650	800	317	3.86	$12.90 \cdot 10^8$	$3.10 \cdot 10^5$
780	850	359	4.08	$15.40 \cdot 10^8$	$3.70 \cdot 10^5$
766	900	403	4.29	$18.15 \cdot 10^8$	$4.36 \cdot 10^5$
879	1000	497	4.66	$24.40 \cdot 10^8$	$5.85 \cdot 10^5$
995	1100	603	4.97	$31.00 \cdot 10^8$	$7.45 \cdot 10^5$
1099	1200	720	5.24	$39.60 \cdot 10^8$	$9.50 \cdot 10^5$
2000	2000	1638	12.30	$212.00 \cdot 10^8$	$50.90 \cdot 10^5$

dust found after the explosion can only be higher than that which could have been produced in the reaction zone of the explosion.

It should be remembered that in the considered example the concentration of coal dust amounted to $q = 76$ g/cu m while the limit concentration of this dust at which propagation of explosion still occurs is $q = 50$ g/cu m.

The quantities of heat released in explosions of coal dust of a lower concentration than the one now considered must obviously be still smaller.

Generally it may be admitted that quantities of heat emitted in more violent explosions, under conditions of a higher dust concentration, might provide a foundation for an explanation of the propagation of explosions. But in the case which is now being considered here, as well as for lower concentrations of coal dust, the quantities of heat emitted are not sufficient to supply a direct explanation of the propagation of explosions. A supplementary explanation is provided by the turbulent movement of the dust.

The very strong turbulent movement which, as a rule, occurs at explosions of coal dust makes possible the development of coal dust explosions.

Explosions of coal dust at concentrations approaching the limit values are possible only when the initiator is very strong. When we refer to coal dust explosions we have in mind the propagation of the explosion — that is, the possibility of its development after the direct influence of the initiator stops to act.

As the initiator of the considered explosion 50 cu m were used of the explosive methane mixture the composition of which had been approximately stoichiometric. The total heat value of the above quantity of the mixture is 39,000 kcal which makes 780 kcal/cu m. This initiator raises coal dust to the air, gives to the entire explosive system an energetic turbulent movement and, naturally, ignites the system.

When the direct influence of the initiator disappears — that is, at a distance of about 100 m from the face of the gallery, the dispersed coal dust releases actually a little less of heat energy during the explosion than the computed value of $Q_s = 470.0$ kcal/cu m.

An explosion can be propagated because particles of dust, yielding tar and gaseous substances, radiate very strongly during the ignition and can cause a propagation of the explosion reaction of coal dust which means the evolution of tar and gaseous products from other particles of the dust; they can also cause a direct ignition of very fine particles of coal dust. This is due to the fact that the just mentioned radiating particles of dust — together with distillation products — move very rapidly in the system of coal dust dispersed in the air, thus acting like firebrands and propagating the explosion reaction in the dust and air mixture. It ought

to be stated that coal dust particles — on account of the differences in masses but also generally — move with velocities different from the velocity of the gaseous medium.

A very active turbulent movement accompanying coal dust explosions plays a decisive role in the propagation of explosions not only in the cases of the dust concentrations approaching the limit ones but also when these concentrations are higher.

As it was already said an equally important role is played by pressure which causes a higher concentration of coal dust in the explosion zone than it would result from a calculation of the quantity of coal dust dispersed uniformly in the cross section of the gallery.

The essentials of the propagation of particularly weak coal dust explosions in which the shock wave does not occur must be elaborated separately. Of special interest are explosions developing with a velocity approaching the regular one of an order of about 50 m/sec. It is quite easy to explain these kinds of explosions when they occur in short sections of galleries. However, explosions of such characteristics have been realized with success in the *EM Barbara* on the entire length of the 400 m experimental gallery. Figure 9.43*b* represents the course of exactly such kind of an explosion. The static pressures during such explosions are very low, 10 to 20 kN/sq m. For the initiation of such an explosion a roof layer of an explosive mixture of methane of 1.5 cu m in volume is quite sufficient.

The pressure educed by the initiator must approach 1 kN/sq m at least because at this value the dust, in the vicinity of the roof accumulation of methane, could be raised in the air as a cloud of sufficient concentration and density. This concerns the case of a particularly easy raising of a coal dust very favorably distributed.

The input of heat energy by the initiator is rather low (about 1200 kcal); the raised primary cloud of coal dust occupies a relatively small space and the turbulent movement inside the cloud is less intensive than it would have been in the case of strong explosions. Nevertheless, an explosion of the kind discussed here is able to be propagated over long distances.

Concentrations of coal dust in clouds in such cases are undoubtedly considerably above the lowest limit concentrations. It is possible that they are close to optimum concentrations not, however, in the whole cross section of the gallery but usually in its roof parts because the optimum dust dispersion conditions are created in order to produce the explosions.

Generalizing, it can be surmised that the propagation of an explosion occurs in consequence of the blast wave producing a sufficient dust cloud concentration in a part of the cross section of the gallery. The pressure of the explosion cannot grow and the flame velocity cannot achieve an accel-

eration since the blast energy is dispersed toward this part of the cross section of the gallery which contains clouds of coal dust of a lower concentration.

Conditions of coal dust distribution must prevent an increase in the pressure in consequence of a deflagration reaction in the cloud of dust.

Nevertheless, even in the very weak explosions discussed here a turbulent movement of the medium occurs without which a development of a coal dust explosion would have been impossible.

Discussing the essentials of the propagation of coal dust explosions at concentrations approaching the limit ones it was possible to estimate, with a high degree of probability, the level of the dust concentration in the whole cross section of the gallery on account of the very strong initiation of explosion used, namely, 50 cu m of an explosive mixture of methane.

In the case of very weak explosions the concentration of coal dust in a cloud is unfortunately not known. It would be very useful to undertake investigations on this subject. Likewise, at least so far, no research work was done in the *EM Barbara* on the dust remaining after the explosions discussed here (it would be desirable to extend investigations in this direction also). In the present state of the inquiries there was no sufficient, experimentally established, data to provide a basis for even an approximate calculation of the quantity of heat liberated in these explosions.

Investigations on the essentials of the propagation of very weak explosions are desirable because the occurrence in the mining practice of very weak explosions is statistically more probable than the occurrence of very violent explosions.

2.3.2.4. Basic physical conditions of coal dust explosions and general information. Flame velocity is a very important parameter of explosions of gases and dusts. Here, it is necessary to distinguish two notions: the velocity of the development of the flame in relation to the explosive medium which, further on, we are going to call the basic velocity, and the velocity of the course of the flame in relation to the walls of the working or of the experimental gallery. This will be called simply the velocity of the flame.

Coal dust explosions can develop by deflagration or by detonation, the latter occurring very seldom (this will be discussed separately).

There are very material differences between the two above mentioned notions of the flame velocity. In order to simplify the elucidation of these differences (and to facilitate the act of comparing them) it is advisable to give, first of all, some information on the velocities of the flame of the

explosion of firedamp which, mixed with air, represents a simple single-phase system.

The basic velocities of the flame of firedamp explosions or, to be more exact, of the course of the flame in the explosive mixture of methane depend upon the percentage content of CH_4 in the air. At any rate, they are very low: for 10.5 percent of CH_4 the basic flame velocity amounts to about 27 cm/sec; for mixtures approaching the lower and the upper limit of explosibility this velocity is found to be about 6 cm/sec [18]. Information concerning these very low values is rather unpopular in mining circles.

Usually the notion of a firedamp explosion is associated with very high velocities of its flame and with consequent great effects of the explosion. The velocities of the flame of a firedamp explosion (in relation to sidewalls of workings or experimental galleries or in relation to walls of the laboratory experimental apparatus) depend on several basic parameters among which one should name in particular: the composition of the explosive mixture and the concentration of CH_4 in the cross section of the working; conditions of expansion of the combustion products of methane; characteristics of the initiation; the condition of the workings or of the experimental installations; and the quantity of the accumulation of the explosive methane mixture. Depending on these parameters the velocities of the flame of an explosive methane mixture of an approximately stoichiometric composition oscillate between several and 800 m/sec. These figures refer to the deflagrational combustion of methane.

In methane explosions of very great importance is the turbulent movement which brings about a marked increase in the quantity of methane burned within a unit of time. It is exactly due to differences in the turbulent movement that the values of the flame velocities, given above as examples, differ so much from each other. For instance, when an explosive mixture of methane is ignited by shotfiring the ensuing flame velocity of the methane explosion and, consequently, its violence are much higher than those produced in the same explosive mixture of methane under the same conditions when ignited, for example, by an electric spark. In this case an important factor is also the movement imparted by the expanding products of the detonation of the explosive to the column of gas in the direction of the development of the explosion.

In coal dust explosions not only chemical reactions but also physical phenomena are much more complicated than in the case of methane. A cloud of coal dust is composed of two phases: a solid, and a gaseous one. In order to create conditions in which an explosion can occur it is necessary to raise coal dust to the air for which a specified energy is required.

The concentration of the dust in the air is usually variable in the cross section of the working. A uniform concentration of coal dust is difficult to maintain even in laboratory conditions. Under conditions prevailing in mines a cloud of coal dust is an intricate and heterogeneous system and, as a rule, it is in a state of turbulent movement. These are the reasons why it is much more difficult to measure the basic flame velocity in a cloud of coal dust than it is in the case of methane. This velocity is estimated at about 1 m/sec [133]. The above value pertains to a cloud of dust of a possibly uniform concentration.

There is a more important difference between coal dust and methane than the one caused by the fact that when we deal with methane we are dealing with a single-phase system in the mixture with air, while in the case of coal dust we have to do with a two-phase system. Unlike methane coal dust is not a distinct chemical compound but a mixture of complicated components the structure of which depends upon the age of the coal. Moreover, it presents different degrees of fineness. Therefore, the basic velocity of the flame is not a conception the value of which can have a general meaning: it refers to a concrete coal of a concrete fineness and in a specified concentration. The velocity given above — that is, 1 m/sec — refers to a coal the properties of which are nearly the same as those of the average Upper Silesian coal. It is quite possible that basic velocities of flame in a cloud of coal dust can be much lower than the given velocity.

The velocity of a coal dust explosion in relation to the walls of workings or experimental galleries, analogically to cases of firedamp explosions, represents the sum of the velocity of the explosion system consisting of the dust clouds and the velocity of the development of the flame in this system.

The blast, which follows the expansion of the products of combustion of coal dust, raises clouds of this dust and thus creates an explosive system. In the case of the lowest limit value of the flame velocity this value is equal to the velocity of the explosive system which is being identified with the velocity of the blast.

As was mentioned already in the preceding section a very important parameter of a coal dust explosion is pressure. There is also a certain minimum pressure necessary to initiate an explosion. Actually this pressure depends on the conditions of the premises in which the explosion takes place. In the case of the experimental gallery at *Buxton*, and in relation to coal dust deposited on the floor, the above mentioned minimum pressure amounts to 12 kN/sq m [134]. In order to create a system capable of propagating an explosion the value of this pressure must reach about double the above minimum.

The information given pertain to very weak explosions initiated by a correspondingly weak initiator.

Continuing the discussion on the physical parameters of the weakest coal dust explosions it should be said that there must exist a certain minimum velocity of the flame of the explosion — we refer here to the velocity of the flame in relation to the roadsides — which is sufficient for the development of an explosion. Below this velocity an explosion cannot develop because it does not create an explosion system since it does not raise coal dust clouds of a sufficient concentration in the cross section of the working.

In the phenomenon of the creation of an explosive system an important role is played by the distribution of the dust in the working. For it is understandable that a considerably lower energy of a blast is sufficient to blow off the dust deposited in the upper parts of workings (on roof support, piping, etc.) than is required to raise the dust from the floor.

When investigating the minimum flame velocity, which would suffice to maintain the development of a coal dust explosion, it was necessary to create such conditions of the distribution of coal dust which made it possible to find the magnitude sought for. With this end in view coal dust had been deposited in such a way as to make its raising to the air through the blast of the initiator as easy as possible.

These conditions, however, wholly corresponded to the possibilities of the distribution of coal dust in mine workings.

On the basis of experiments made in the *EM Barbara* it is possible to state that the minimum velocity of the flame of a coal dust explosion amounts to about 30 m/sec. At some place this velocity may be lower amounting to 20 m/sec. An explosion with a velocity approaching a uniform velocity amounting to about 30 m/sec throughout a rather long road is a rare phenomenon in mining conditions and also difficult to be obtained under experimental conditions.

Ordinarily an explosion, having moved a certain distance with this velocity, either fades away or shows an acceleration often a very marked one.

It is worth noticing that theoretical calculations of the velocity of the flame at minimum pressures amounting to about 0.12 kN/sq m give the value of this velocity which is very close to the value determined experimentally in the *EM Barbara*.

As the result of many years of investigations conducted in the *EM Barbara* it is possible to state that the maximum flame velocity at a deflagrational reaction of an explosion of coal dust may be slightly in excess of 1000 m/sec. This value comes close to the results of theoretical calculations.

In explosions of coal dust a great role is played also by the dynamic pressure exerted on surfaces perpendicularly placed in relation to the direction of the blast. The velocity of the blast is related with the velocity of the flame. As a result the dynamic pressure depends upon the flame velocity.

Taking this fact into account investigations were conducted in the *EM Barbara* on the correlative dependence between the flame velocity and the dynamic pressure under conditions of the weakest coal dust explosions [62]. The results obtained are presented in the form of graphs in Fig. 2.19. In this figure, apart from the regression curves obtained as the results of the experiments, a curve is given representing the results of theoretical calculations [111]. The difference in the shape of the curves is due to simplified assumptions adopted in theoretical calculations in which the increase in the density of the medium, resulting from the presence in it of coal dust, was not taken into consideration.

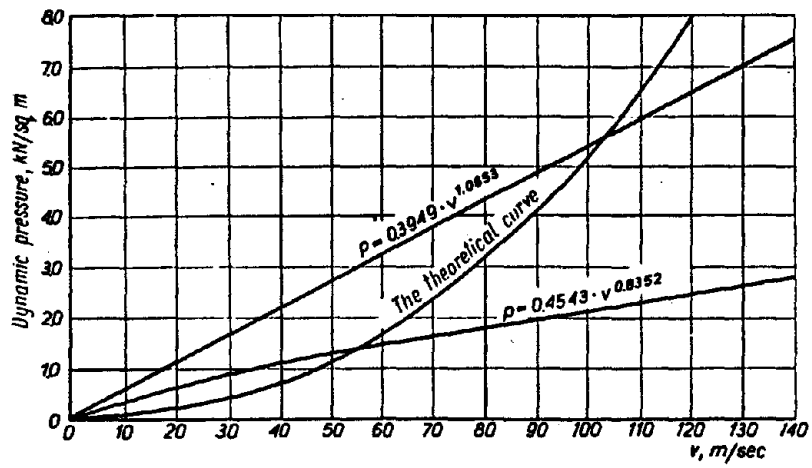


Fig. 2.19. The dependence of the dynamic pressure upon the velocity of the flame of very weak coal dust explosions.

In Table 2.8 the calculated average dynamic pressures p are listed as well as the maximum dynamic pressures P for the average velocities of the flame of coal dust explosions from 20 to 100 m/sec.

The obtained correlation dependences are of great value in the investigations concerning the possibility of putting barriers into action under conditions of very weak explosions of coal dust. This problem will be considered later on.

In very weak explosions of coal dust no shock wave is created. But it occurs always when coal dust explosions are more violent and is initiated easily by strong explosion initiators such as, for example, an explosion of firedamp. It comes into being also when there is a sufficient accelera-

tion of the flame; this question will be discussed in more detail when presenting the mathematical model of coal dust explosions.

An explosion of coal dust may have a detonative character which means that the explosion reaction may be initiated by a shock wave.

Table 2.8

The Average Dynamic Pressures p and the Maximum Dynamic Pressures P for the Average Flame Velocities

Dynamic pressure	Flame velocities V, m/sec							
	20	30	40	50	60	70	80	100
p, N/sq m	550	780	990	1190	1390	1580	1770	1950
P, N/sq m	960	1480	2010	2550	3100	3650	4210	5330

A detonation of coal dust causes very far-going destructions in the experimental galleries. For this reason no special experiments were made to investigate this phenomenon. Nonetheless, in the course of numerous experiments carried out in the *EM Barbara* there were ascertained such developments of coal dust explosions which can be classified as detonative explosions. The flame velocity in these cases reached about 2000 m/sec. According to theoretical calculations [111] the velocity of coal dust detonation D may amount to 2300 m/sec, the pressure of the detonation P_D = = 2700 kN/sq m, the temperature of the detonation T_D = 5273°K (5000°C).

While, naturally, during explosion disasters in mines no measurements are taken of either flame velocity or pressure yet, on the basis of the descriptions of the course of explosions and their effects, it cannot be established that under conditions prevailing in mines a detonation of coal dust had ever occurred. Nevertheless, such an occurrence is quite possible. A case illustrating such a possibility will be described when we shall discuss investigations concerning the possibility of a coal dust explosion developing in the direction of blind ends. Further considerations of the problem of coal dust explosions will refer, in principle, to their deflagrational course.

A coal dust explosion can have an oscillatory nature as the result of the resonance of the gas column in a gallery. In the experimental gallery of the *EM Barbara*, as well as in mine roadways, such explosions are not possible because of the support and of the uneveness of the roadsides.

2.3.3. A mathematical model of coal dust explosions

The phenomenon of a coal dust explosion is considerably more complicated than the phenomenon of explosions of gaseous systems. A presen-

tation of even a simplified mathematical model of a coal dust explosion requires the introduction of many simplifications.

A reaction bound up with an explosion of a gas is always a very complicated chain reaction even in the case of a detonation of the mixture of hydrogen and oxygen but, when gases explode we always deal with a single-phase system and, moreover, it can be always possible to examine truly homogeneous mixtures of gases. The end products of explosive reactions of gases are strictly specified since they are very easily determined experimentally. In consequence the amount of the heat of energy emitted in such cases can be easily calculated.

The turbulent movement within the system of a coal dust cloud in the air has a tremendous influence on the course of an explosion; it should be remembered also that the movement of the grains of dust of different masses is very complicated. The present author knows of no studies of any precision on this subject. The reaction or, more properly, reactions between the oxygen of the air and the products of the pyrolysis of the coal substance are exceedingly involved. Likewise, the products of a coal dust explosion are difficult to determine and, consequently, the quantities of heat energy emitted in a coal dust explosion cannot be determined with such certainty as in the instances of explosions of gaseous systems.

First efforts of working out a mathematical model of coal dust explosions were made by Taffanel [166]. Many years ago a mathematical model had been given by Artingstall [1]. The works carried out on this subject were supplemented by Lebecki [11] who based his contribution on the very large material obtained experimentally by the present author.

2.3.3.1. A simplified mathematical model of the motion of gases during coal dust explosions. The course of a coal dust explosion is so intricate as a phenomenon that, in order to elaborate its mathematical model, certain simplifications must be introduced of which the most important are the following two: the consideration of the phenomenon in one dimension only and the assumption that the zone of the flame is of a much shorter length than the length of the gallery. The adoption of the one-dimensional point of view means that one resigns consciously from the consideration of the phenomena of the turbulence of gases (which unquestionably exist), while the assumption that the zone of the flame is narrow means that one does not examine the phenomena of the pyrolysis and of the combustion of the separate grains of dust but regards the flame as a zone in motion in which chemical reactions of combustion take place. The adoption of the above two assumptions makes possible the elaboration of a mathematical model which, with all its imperfections, is very useful for analyzing the phenomenon of a coal dust explosion. In Fig. 2.20 a situation is presented schematically which comes into being directly when — after the initiation

of an explosion — the flame front is formed (A_1A_2) ahead of which the raised coal dust hangs in the air. Behind the front of the flame postreaction gases and unburned grains of dust are found. At the face of the gallery the velocity of the gas in relation to the walls of the gallery must amount to zero and on the basis of the principle of the continuity of state

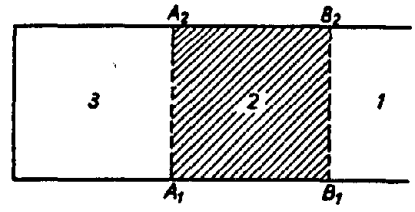


Fig. 2.20. A diagram of the pressure wave formation.

in the whole zone *3* gas must be motionless in relation to the walls of the gallery. In zone *2* gas moves with a velocity equal to the difference between the velocity of the flame in relation to burned up gases and the basic velocity described in Section 2.3.2.4. But at the same time at a big distance from the zone of the flame, gas is motionless and is not under the influence of the movement of the flame. This contradiction is only a seeming one because, ahead of the flame front, a surface of discontinuity is created (B_1 B_2) which divides the region ahead of the flame front into two zones: *1* and *2*.

The surface of the discontinuity, in other words, the surface on which the parameters of the thermodynamic state — that is, the pressure, density and temperature of the gas change in jumps, may represent either a pressure wave or a shock wave. The pressure wave is described by the Euler motion equations for continuous media. To avoid any misunderstandings it is necessary to explain that the term "wave" does not denote in this case a phenomenon occurring periodically in either time or space, but a single impulse of pressure propagating itself with a certain velocity in a medium. The Euler equations give only the most general form of the equation of the pressure wave which can be useful in practice only when a specified relation between the pressure and the density (or the volume) of gas is adopted. Such relations do exist in the form of equations of the state of gases and equations of thermodynamic processes. A superficial analysis of the explosion phenomenon shows, however, that the most sensible thing is to regard the gases, which participate in the explosion, as perfect gases (that is, fulfilling the Clapeyron equation) and the thermodynamic processes as adiabatic (that is, fulfilling the Poisson equation). This is justified by the fact that deviations from the Clapeyron equation manifest themselves only in the presence of near-critical states and in

very high temperatures, densities and pressures (for example, in the process of the detonation of explosives) which do not occur in coal dust explosions. The adiabaticity of the process of a coal dust explosion is likely to arouse more doubts but it is the nearest of all possible known approximations. In practice this assumption means that the process evolves under the protection of a nonabsorbing heat shield or that it evolves so rapidly that no heat exchange occurs with the environment. The second alternative often happens to be true in coal dust explosions particularly when they are strong.

The application of the Poisson adiabate equation to the pressure wave gives the following relationships:

— for the static pressure behind the front of the pressure wave

$$P_{st} = P_{0st}\left(1 + \frac{\gamma - 1}{2} \cdot \frac{u}{c_0}\right)^{\frac{2\gamma}{\gamma - 1}} \tag{2.8}$$

where

P_{st} — the static pressure behind the front of the pressure wave,

$P_{0\,st}$ — the static pressure ahead of the front of the wave,

c_0 — sound velocity ahead of the front of the wave,

u — gas velocity behind the wave,

γ — the adiabatic constant $= \frac{c_p}{c_v}$;

— for the gas density behind the front of the pressure wave

$$\varrho = \varrho_0\left(1 + \frac{\gamma - 1}{2} \cdot \frac{u}{c_0}\right)^{\frac{2}{\gamma - 1}} \tag{2.9}$$

where

ϱ — gas density behind the wave,

ϱ_0 — gas density ahead of the front of the wave.

For a given velocity of gas it is possible to calculate the static and dynamic pressure (taking into account that dynamic pressure is equal to $P_{\text{dynamic}} = \frac{\varrho u^2}{2}$). For the purpose of the calculation it can be accepted that $\gamma = 1.4$ (the mean value for the air).

The calculated parameters are valid for weak explosions. The sound velocity c, in conditions corresponding to the pressure and density of air in a pressure wave, is given in the formula

$$c = c_0 + \left(\frac{\gamma - 1}{2}\right) \cdot u \tag{2.10}$$

In the consideration of weak explosions the following approximations are useful

$$P_{st} = 0.41u \quad \text{and} \quad P_{st} = 17\sqrt{P_{dynamic}}$$

These approximations are obtained through the series expansion of (2.8) and (2.9) and the insertion of 1.4 for γ; 1.23 kg/cu m for ϱ_0; 10^5 kN/sq m for $P_{0\,st}$.

In Table 2.9 are given calculated numerical values of sound velocity, density, static and dynamic pressures for the given value of the gas velocity behind the wave u (the velocity of the blast) and the same values determined experimentally for weak explosions of coal dust in the 400 m gallery in the *EM Barbara*; explosions were initiated by roof accumulations of explosive firedamp mixtures. In some instances a very good conformity between the calculated values and the values determined experimentally can be observed.

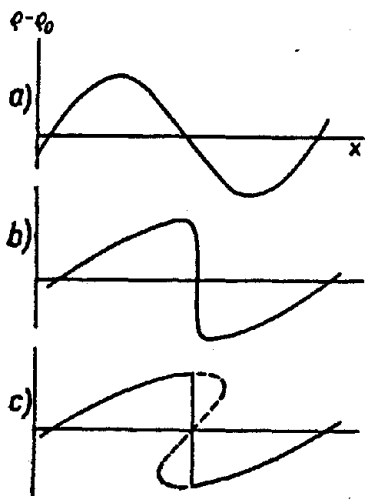


Fig. 2.21. A diagram of the shock wave origination.

The velocity of the propagation of waves in relation to roadsides, denoted by U, is the result of the superposition of sound velocity c over gas velocity u, thus

$$U = c + u \qquad (2.11)$$

The velocity of the propagation of the wave U represents a growing function of the gas density. Therefore the profile of the wave, or the spatial distribution of the density and pressure, is variable in time since elements of increased density move quicker and those of lower density — slower. In consequence a situation might be created that the spatial distribution of pressure and of gas density in the wave would have become equivocal (meaning that at one and the same place gas would have two different densities which is obviously impossible) and this is why a shock wave comes into being (Fig. 2.21). In Fig. 2.21*a* a graph is given showing the changes in the density of gas in the pressure wave as a function of the position of x. The difference is measured in relation to ϱ_0. As places at which the density is high (compressions) shift more quickly than rarefactions a situation is created, as shown in Fig. 2.21*b*, in which again if a shock wave were not created (a perpendicular continuous line in Fig. 2.21c) an equivocality would have occurred. In a concrete instance of a coal dust explosion a shock wave can be created immediately if the explosion is strong or it may occur after a certain time in a weak explosion.

Table 2.9

Theoretical and Experimental Characteristics of Pressure Waves in Weak Coal Dust Explosions in the 400 m Gallery of the *EM Barbara*. The Explosions Were Initiated with Roof Accumulations of the Explosive Mixtures of Methane

Number of test	Flame velocity m/sec	Range of measurement m	Flame acceleration m/sec²	Computed blast velocity m/sec	Computed sound velocity m/sec	Experimentally found pressure wave velocity m/sec	Static pressure N/sq m		Dynamic pressure N/sq m	
							computed	experimental	computed	experimental
1182	47.6	10–240	+9.6	20	344	360	8250	10,000	280	500
1270	131.0	100–320	+80.6	25	345	370	11,800	14,000	1000	630
1299	72.0	30–360	−2.8	40	348	390	16,000	16,200	1240	1700
1188	67.6	10–280	+17.1	50	350	400	20,000	21,000	1950	2000
1273	103.2	20–200	+17.1	60	362	410	24,200	25,000	3020	3500
1433	66.0	10–60	+81.0	80	356	440	31,800	32,000	5460	5000
	100.0	80–120								
1417	47.0	10–280	+4.0	90	358	450	35,700	36,000	7130	6000
1413	42.0	10–160	−9.8	100	360	460	39,500	40,000	9600	116,000

The time in which a shock wave comes into existence is represented by the following formula

$$t = \frac{2c_0}{a(\gamma + 1)} \tag{2.12}$$

where a denotes the acceleration of the flame velocity.

When explosion initiators are strong the ensuing accelerations are high and this facilitates very considerably the creation of a shock wave. On the other hand when the initiators are weak and, generally, when accelerations are low a shock wave will also come into being but only after a relatively long time which means that the flame will have traveled already a long way.

The magnitude of the acceleration can be expressed by the formula

$$a = \frac{2c_0^2}{x(\gamma + 1)^2} = \frac{5.88 \cdot 10^4}{x} \text{ m/sec}^2 \tag{2.13}$$

where x denotes the way traveled by the flame.

According to the above formula the shock wave comes into being after the flame has traveled:

$x = 100$ m when $a = 388$ m/sec^2
$x = 200$ m „ $a = 194$ m/sec^2
$x = 300$ m „ $a = 129$ m/sec^2

Of course a shock wave will not be created at a uniform motion. After the flame has traveled only a short distance high acceleration rates are necessary for creation of a shock wave.

Properties of a shock wave may be itemized as follows:

— the velocity of the propagation of a shock wave is always higher than the sound velocity in undisturbed medium;

— a shock wave is not periodical in its character and it propagates itself in the form of a surface of discontinuity perpendicular to the direction of motion;

— in the shock wave front the parameters of the state and motion of gases change stepwise; actually this is not very exact; a shock wave is not a perfectly flat formation and the layer of it that constitutes the section within which the motionless gas is transformed into a gas in motion has a certain thickness; according to the theory of shock waves the thickness of the wave is the smaller the more abrupt is the jump of the pressure $\frac{\Delta p}{\Delta t}$;

— the passage of the shock wave is connected with the movement of the medium in the direction of the movement of the wave.

During an explosion in which a shock wave has been created (Fig. 2.22) the gallery may be divided into three zones. In zone *1* the pressure

is p_0, the air density and sound velocity are ϱ_0 and c_0, respectively, and temperature is T_0. Behind the shock wave (zone 2) the analogous magnitudes are marked with the index 1, and behind the front of the flame (zone 3) with the index 2.

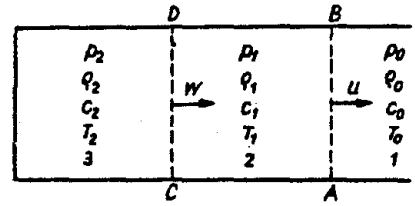


Fig. 2.22. A diagram of an explosion creating a shock wave.

The wave and the flame are surfaces on which stepwise changes of the parameters of state occur and the laws of the conservation of mass, energy and momentum are binding. It is possible to deduce all the necessary interdependences from these laws adopting, for instance, shock wave velocity U_d as the independent variable. Thus the gas velocity behind the wave u_1, or the blast velocity in relation to the gallery walls, amounts to

$$u_1 = \frac{2}{(\gamma+1)} \cdot \left(\frac{U_d^2 - c_0^2}{U_d} \right) \tag{2.14}$$

and the density

$$\varrho_1 = \frac{\varrho_0 U_d}{U_d - u_1} \tag{2.15}$$

The sound velocity behind the wave

$$c_1 = U_d \sqrt{\frac{\varrho_1(\gamma+1)}{U_d^2(\gamma-1)+2c_0^2}} \tag{2.16}$$

The static pressure behind the shock wave

$$P_{1st} = P_{0st} + \frac{2\varrho_0(U_d^2 - c_0^2)}{\gamma+1} \tag{2.17}$$

Temperature behind the wave front

$$T_1 = T_0 \cdot \left(\frac{\varrho_0}{\varrho_1} \right) \cdot \left(\frac{P_{1st}}{P_{0st}} \right) \tag{2.18}$$

Flame velocity is determined as a function of the heat of combustion of coal dust by solving a square equation which is rather intricate as a computing task.

The pressure behind the flame front amounts to

$$P_{2st} = P_{1st} - \varrho_1 u_1 (W - u_1) \tag{2.19}$$

where W denotes the velocity of the flame.

The following conclusions can be drawn from the equations of the conservation of mass, energy and momentum:

— $W > u_1$ which means that the flame moves with higher velocity than gas behind the shock wave; this is quite logical since — if it were otherwise — no oxygen could have been supplied to the flame;

— $P_{1\,st} > P_{2\,st}$ which means that pressure behind the front of the flame is lower than ahead of it;

— for weak shock waves the following relation occurs

$$U_d = c_1 + u_1 \tag{2.20}$$

which means that the velocity of a slowly moving shock wave represents the sum of sound velocity and of the gas velocity behind the wave in the same way as it happens in the case of pressure waves; the situation here described occurs most frequently in coal dust explosions in which shock waves were created.

Registered pressures of explosions indicate whether during an explosion a shock wave was, or pressure waves were, created. A pressure gauge placed at a given place and registering the changes in the pressure in the course of time shows a strong increase in the pressure from the atmospheric pressure (the value of which in the recording devices is marked as 0) to the maximum value occurring within several milliseconds. If such an increase is slow we are dealing with a pressure wave. If, on the other hand, the increase in the pressure is abrupt it indicates the existence of a shock wave. In Fig. 2.23 a typical example of the registration of the static pressure in the experimental gallery of the *EM Barbara* is shown. In the first phase of the explosion the pressure increases slowly but beginning from the 160th m of the gallery a sharp increase in the pressure is observed (explosion No. 952).

The formulas obtained for the separate parameters of explosions make

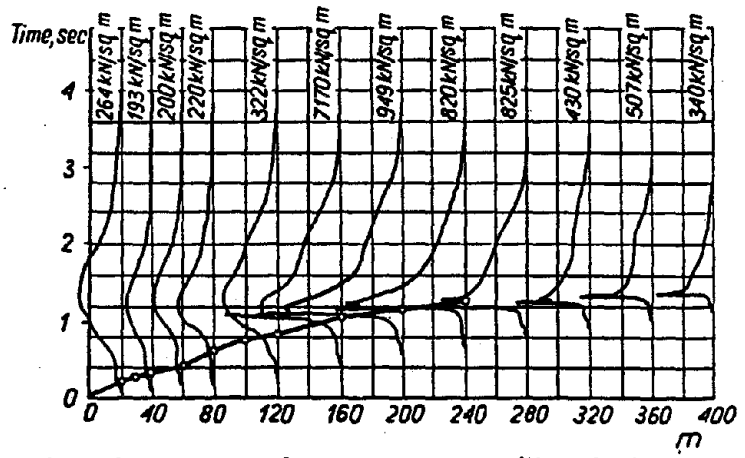


Fig. 2.23. A passage of a pressure wave with a shock wave.

possible to compile in Table 2.7 these parameters for different velocities of the shock wave. In the calculation the following values were applied: $\gamma = 1.4$; $c_0 = 340$ m/sec; $\varrho_0 = 1.23$ kg/cu m; $P_{0\,at} = 105$ kN/sq m. The selected range of the changes in the parameters is considered to be typical for coal dust explosions.

2.3.3.2. Aerodynamic phenomena occurring in experimental galleries and in mine workings. The data given above concerning pressure waves and shock waves pertain to galleries of infinite lengths. This simplification is a very serious one and, therefore, it is necessary to examine a few real instances of the movement of pressure waves in mine galleries.

Of essential importance are the following instances:

The passage of a pressure wave to the open atmosphere. The open end of a gallery is characterized by the fact that the pressure there is permanently equal to the atmospheric pressure so that the pressure of the incident wave p_1 falls to p_0 and the wave of this lower pressure propagates itself in the direction of the closed end of the gallery as the reflected rarefaction wave. The gas velocity in the reflected wave is twice as high as the gas velocity in the incident wave. The direction of the movement of the gas is the same as the direction of the incident wave. This is an essential feature because in such cases the rarefaction wave causes an acceleration of the movement of the flame (the phenomenon can be figuratively described as the "drawing in" of the flame by rarefaction wave).

The reflection of a pressure wave from a rigid wall. In this case an incident compression wave produces a reflected compression wave, and an incident rarefaction wave produces a reflected rarefaction wave. The gas velocity after the reflection will be close to zero while the pressure will grow. It follows that the flame moving in the direction of the rigid wall begins — after the reflection — to move in an almost motionless environment and, therefore, the quantity of oxygen supplied to the flame front diminishes so that the flame reduces its velocity and is eventually extinguished. The pressure behind the reflected wave grows.

The passage of pressure waves through a gallery with variable cross sectional areas. When a wave passes from a gallery with a smaller cross section to a gallery with a larger cross section the gas velocity decreases and, in consequence, the flame velocity diminishes as well. In a reversed situation an acceleration of the flame is obtained. The wave reflected from the narrower sector of the gallery is a compression wave. The flame moves with a diminished velocity when it approaches the surface at which the size of the cross section changes and it accelerates its movement rapidly in the narrower gallery.

Coal dust explosions are investigated, for obvious reasons, in experimental galleries to which references were made already on numerous oc-

casions. In principle, experimental galleries ought to reproduce actual mine conditions so nearly as to make the conclusions drawn from experiments applicable in the mining practice. This requirement is best satisfied by experimental galleries in underground mines. Experimental mines can have such galleries.

In the majority of cases tests are conducted in experimental galleries built on the surface in the form of either steel tubes or reinforced concrete structures. During an explosion in such galleries one can usually observe that, after the eruption of coal dust clouds blown by the blast moving ahead of the flame, a rarefaction wave is created. This wave is visible since it causes the drawing in of a part of the ejected coal dust cloud which moves back into the interior of the gallery. The rarefaction wave moves inside the gallery in the direction of the gallery's face. As the result a reflected wave is created in the gallery moving again toward the gallery's outlet. This phenomenon can also be observed through hearing a sound as if the gallery were "breathing." The frequency of this sound depends on the length of the gallery.

The above described phenomenon of the rarefaction wave does actually influence the course of a coal dust explosion in a surface gallery.

Various shapes of the cross sections of experimental galleries, described by Ramsay [136] and supplemented in the book, are presented in Fig. 2.24.

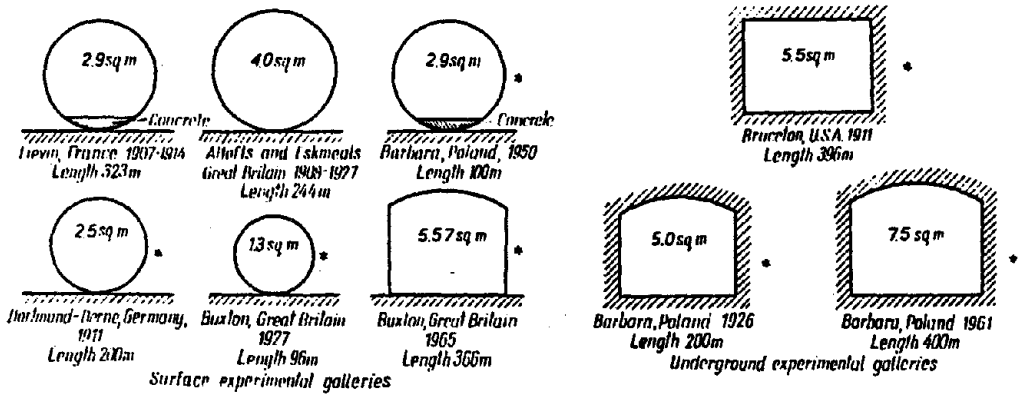


Fig. 2.24. Cross section areas and lengths of experimental galleries after H. T. Ramsay supplemented by information on new experimental galleries in the *EM Barbara*, *Buxton* and the *Tremonia* mine. Note: * — experimental galleries still active.

Artingstall had paid special attention to the course of explosions in experimental galleries calling the rarefaction wave the reflected wave [1], [2]. He presented a very interesting diagram of the course of the shock

wave, of the blast of the flame, and of the reflected wave in a surface experimental gallery as shown in Fig. 2.25. The rarefaction wave, moving in the direction opposite to that of the flame, causes an acceleration of the movement of the flame and, in consequence, when stone dust barriers are examined the results obtained might differ from those which would have been obtained under conditions corresponding to those found in mines; of course, this is true only in cases in which the barriers are located within the influence zone of the rarefaction wave.

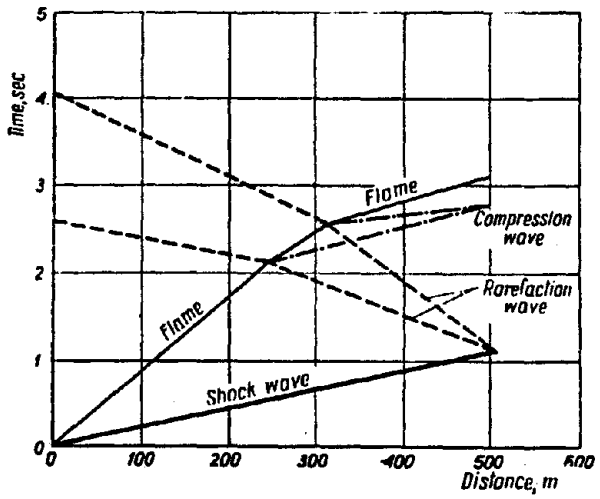


Fig. 2.25. An approximate qualitative diagram of the course of a (deflagration) explosion in a gallery of a definite length (after Artingstall).

In connection with Artingstall's theory at *Buxton* in Great Britain very penetrating investigations were carried out on the course of the above phenomena in an experimental gallery 366 m long. As the result of these investigations it was established that only up to the distance of 100 m the course of the explosion is not influenced by the rarefaction wave. It should be mentioned here that the experimental gallery at *Buxton* has no support and its walls are smooth.

In the *EM Barbara* the present author, despite a very careful examination of a very large number of graphs representing courses of explosions, could find no clear evidence of an influence of the rarefaction wave upon the course of explosions nor upon the results of testing the efficiency of stone dust barriers and water barriers. The reason of this lies probably in the fact that experimental galleries are situated at the depth of 44 m under the surface and their outlets, which reach the surface, represent rise galleries. A certain role could also be ascribed to the steel support of the galleries.

However, when the course of coal dust explosion had been examined propagating itself in the direction of the blind face of the gallery it was established in the *EM Barbara* that the influence of the rarefaction wave upon the course of the explosion phenomenon was very manifest. This will be discussed later on in the relevant chapter.

In underground mines the influence of rarefaction waves — analogous to that observed in surface experimental galleries — is out of the question.

The phenomena of reflected waves and also of rarefaction waves (after the passing of explosion blast) are, under conditions prevailing in mines, very complicated on account of the great diversity of the networks of workings.

Returning once again to the question of the influence of the rarefaction wave upon the course of explosions in the experimental gallery of the *EM Barbara*, note that this influence might actually exist at the very end of the gallery where a considerable acceleration of the flame velocity occurs at times which may be actually due to the influence of the rarefaction wave. In mine workings, as well as in experimental galleries, the cooling of gases also has a strong influence on their motion. A period of time just above a couple of seconds can suffice — depending on conditions — to bring about a negative pressure and, in consequence, the suction phenomenon.

2.3.3.3. The phenomenon of coal dust detonation. This phenomenon consists in the initiation of a detonation reaction in the explosive medium of dust or gas by a shock wave which means, in practice, that the shock wave and the flame velocities are equal. The phenomenon of detonation differs from that of deflagration also in this that the products of the reaction move in the same direction in which the detonation wave is moving while in a deflagration reaction the products of the reaction move in the direction opposite to that of the deflagration front.

The problem of the possibility of a detonation of coal dust has been rather seldom mentioned in the publications of investigators studying coal dust explosions. Generally it can be claimed that nothing concrete has been uttered in this matter. As far as experimental results are concerned no investigator had established in his experiments — up to the present time — a detonation of coal dust. The occurrence of this phenomenon was established recently in the *EM Barbara* when the present author was in the course of writing his book (*Biuletyn PAN*, No 5, 1971).

The detonation of the d25 coal dust had been established unexpectedly when the possibilities of the development of a coal dust explosion in the direction of the blind end of the 400 m experimental gallery were examined.

According to calculations (formula 2.18) temperatures within the range

of a shock wave are sufficient to ignite the dust only if the waves possess high velocities. These, and many other factors, are responsible for the fact that the phenomenon of detonation occurs very seldom and, up to a certain time, was considered to be practically impossible. The experiment carried out in the *EM Barbara* supplied the evidence that the phenomenon is a concrete possibility.

The maximum velocity of detonation is expressed by the formula

$$D = \sqrt{2Q - \frac{2c_0^2}{(\gamma - 1)}} \tag{2.21}$$

where

Q — the combustion heat, J/kg,

c_0 — sound velocity amounting to 340 m/sec.

For $Q = 2.7 \cdot 10^6$ J/kg the value $D = 2200$ m/sec.

The detonation of coal dust occurs most frequently above the so-called Jouguet point which is characterized by the fact that the gas velocity behind the detonation wave is equal to, or lower than, the velocity of sound in that gas while it is always supersonic in relation to the gas which is ahead of the wave. The detonation velocity corresponding to the Jouguet point amounts to

$$D_j = \sqrt{2(\gamma^2 - 1)Q} \tag{2.22}$$

For the parameter values similar to those previously given this velocity is: $D_j = 2130$ m/sec.

3. MAIN PARAMETERS OF THE EXPLOSIBILITY OF COAL DUST

3.1. THE ROLE OF VOLATILE MATTER IN THE EXPLOSIBILTY OF COAL DUST

3.1.1. General information

All investigators of the explosibility of coal dust, headed by Taffanel, have established since long ago that the contents of volatile matter in coal are a decisive factor in the explosibility of coal dust.

Volatile matter evolves from coal as the result of the thermic decomposition of coal without the access of air. Though in the case of a coal dust explosion air has access to particles of the dust yet the evolution of the volatile matter constitutes a pyrolysis during which the chemical and physical structure of coal undergoes a far-going change. Bituminous coal is decidely a thermolabile substance.

During a pyrolysis the liquid and gaseous substances are evolved and coke remains. The difference in the weight of coal prior to, and after, being heated to a specified temperature of 1123°K (850°C) under specified conditions denotes the content of volatile matter. The volatile matter is the product of chemical reactions — that is, decomposition of heated coal substance and of many secondary complicated reactions that take place between the evolved products. Only the absorbed water and physically occluded gases, which are evolved at relatively low temperatures, are the primary components of coal [146].

In the process of the pyrolysis of coal at high temperatures there are two stages to be distinguished: the first stage consists in the thermic decomposition of the coal substance, during which the primary products of this decomposition are evolved, while during the second stage secondary reactions occur between the primary products. The first stage of the decomposition of the coal substance undoubtedly originates the appearance of free radicals.

The whole pyrolysis process is very complicated. The chemical composition of the volatile matter depends in a large measure upon the temperature.

The volatile matter content is usually computed in relation to the d.a.f. coal substance. This magnitude constitutes a very characteristic and important property of coal. In the problem of the explosibility of coal dust exactly this magnitude is of paramount importance.

As an example the volumetric composition is given hereunder of the volatile matter contained in the typical Upper Silesian coal when very abruptly, and during a very short time, it is heated to the high temperature of 1173°K (900°C): hydrogen 18.39%, carbon monoxide 73.40%, carbon dioxide 2.80%, methane 4.38%, ethane 0.32%, propane 0.08%, propylene + isobutane 0.33%, hydrogen sulfide 0.30%.

When in a cloud of coal dust a thermic factor appears of a sufficiently high temperature it causes, first of all, the evolution of volatile matter from the coal dust. The most common thermic factors which come into play in mining processes are: the flame of a firedamp explosion, the flame of the detonation products of explosives, the electric arc, or any kind of flame in general. Under the impact of a high temperature of the flame the evolution of volatile matter of coal dust is of fundamental importance. With a given thermic factor the quantity of volatile matter evolved from a unit of weight of the dust within a unit of time depends on the degree of fineness of the coal dust.

In the course of a photographic observation of the process of combustion of single grains of dust two phases of the combustion were distinguished: in the first phase volatile matter is burned, and in the second phase the remaining coke is consumed by fire and this takes 20 times longer than the burning of the volatile matter.

Naturally the time of combustion depends upon the size of the grains, for example, a grain of the dust whose specific surface is 1000 sq cm/g shows 1.4 millisec as the time in which its volatile matter is burned, while the same process in the case of a grain of dust of a specific surface of 510 sq cm/g takes 7.6 millisec [81].

The processes of combustion of the products of pyrolysis and of the coke residue in the course of a coal dust explosion are very involved Very small particles of coal dust may be completely burned up.

Ordinarily in the course of an explosion there is too much coal dust in relation to the oxygen contained in the air. As the result of this, always after the passage of the explosion flame a mixture of gases is formed in which the following gases appear in particular: carbon monoxide, carbon dioxide, methane, hydrogen and also, in smaller quantities, various hydrocarbons.

In the *EM Barbara* numerous examinations were made of gaseous products directly after coal dust explosions and it was established that the composition of gases varies very widely depending on the character

of a given explosion. Particularly noxious role plays carbon monoxide which appears after explosions.

In the experimental galleries of the *EM Barbara* the maximum concentrations found were: 10.8% CO, 15% CO_2, 3.7% H; the minimum ascertained concentration of oxygen was 0.1%.

Many examinations of the coke residue were made. We are going to discuss the results of these examinations when the nature of coal dust explosions will be considered.

3.1.2. The dependence of the explosibility of coal dust on the content of volatile matter $S = f(V)$

On account of the great role played by volatile matter in the explosibility of coal dust many investigators dealt, in various aspects, with the problem of the dependence of the explosibility of coal dust upon the content of volatile matter. In the *EM Barbara* within a long period of time many investigations were carried out on this subject. Research works were conducted in the period between the wars as well as — on a very large scale — in the postwar period at first in the surface experimental gallery and, later, in underground galleries. The summing up of the results of these researches are given in two publications [40] and [55]. Altogether there were 1134 investigations on a large scale made in the *EM Barbara* in which coal dust was used from 43 coal seams from Polish coal fields and also from several foreign coal basins.

3.1.2.1. Conditions of investigations. In these investigations two explosion initiators were used: 30mPII and 50 cu m CH_4.

The 30mPII initiator consisted in the explosion of coal dust from the seam 314 of the *EM Barbara* containing 41 percent of volatile matter and consisting in 85 percent of the 75 μm fraction. This dust, called the *d*85 dust, was deposited on a 30 m sector of the experimental gallery under conditions of the easiest dispersion. The explosion was initiated by firing a charge of 750 g of black powder from a mortar. This has been the strongest initiator employed in the course of investigations conducted in the *EM Barbara*.

The 50 cu m CH_4 initiator consisted in the explosion of 50 cu m of the mixture of methane with air, the content of CH_4 in the mixture varying from 8 to 9.5 percent. To explode the mixture a charge of 750 g of black powder is fired from a mortar. The explosive mixture of methane was prepared in a methane chamber separated from the gallery by a paper diaphragm.

To simplify the terminology the explosive mixture of methane with

air will be called hereafter in this book: methane. Only when considering other concentrations of methane in the air the percentage of CH_4 will be indicated.

Figure 5.7 shows both the range and the velocity of the flame for the two initiators.

The initiator 30mPII has been considered as the strongest among those that could be employed and suitable for the basic investigations on the explosibility of coal dust.

The initiator 50 cu m CH_4 is slightly weaker than 30mPII. It was used because the classical initiator of coal dust explosions in mines is most frequently a local explosion of methane. In the circumstances it was thought advisable to examine the function $S = f(V)$ also under such conditions.

The examined coal dust was deposited in the experimental gallery beginning from the zone of the initiator.

In all examinations of the function $S = f(V)$ the coal dust used was dry — that is, containing only very insignificant quantities of free water (about 1 percent). The dispersibility of this dust was very high.

The conditions of dispersion in all investigations discussed here were the easiest possible: coal dust was deposited on top of the roof bars in the gallery. Moreover, when these experiments were carried out one tried to ensure the optimum concentration of dust for the propagation of explosions.

The *d*85 coal dust (fine) containing 85 percent of the fraction < 75 μm, and *d*25 coal dust (medium) containing 25 percent of this fraction were used in the experiments.

These two kinds of coal dust were used in many experiments conducted in the *EM Barbara* as standard (model) kinds, and this for practical reasons.

The *d*85 coal dust is found in our mines not very often yet it can be regarded as the average upper limit of the fineness of coal dust in our mines.

The *d*25 coal dust is found in our mines relatively often and this fineness of the dust may be considered as quite common.

In the end the investigations have led to the finding of the functions $S = f(V)$ for the following four sets of conditions:

(1) the *d*85 coal dust, initiator 30mPII,
(2) the *d*85 coal dust, initiator 50 cu m CH_4,
(3) the *d*25 coal dust, initiator 30mPII,
(4) the *d*25 coal dust, initiator 50 cu m CH_4.

When considering the value of S as solid incombustible matter were regarded the contents of ash in the coal, of hygroscopic moisture and of

limestone dust accurately mixed with coal dust. The limestone dust contained about 60 percent of fraction < 75 μm.

The investigations discussed now were spread over a period of 12 years. For this reason it was not possible to determine the values of S by the same number of experiments. The number of experiments which ended in the nonpropagation of the explosions with the content of solid incombustible matter S oscillated between 2 and 15 and amounted, on the average, to four. The experiments were carried out with the percentage of incombustible solid matter contained in coal dust differing by 2.5 percent from that contained in the coal dust used in the preceding experiment in the effort to keep the accuracy of denotations of S within 2.5 percent limit.

Apart from determining the value of S, called the degree of the explosibility of coal dust, the already mentioned explosibility indices Z were also found. In the experiments now under consideration 60 samples of coal were used taken from seams in which the content of volatile matter varied from 8.5 to 61 percent. Coals in which the content of volatile matter exceeds 45 percent belonged to the so-called sapropels.

The experiments were conducted in the experimental gallery 200 m long, the cross sectional area of which is of 5 sq m. Supplementary experiments were carried out in a 400 m gallery the cross sectional area of which is 7.5 sq m, a circumstance discussed in a separate chapter.

3.1.2.2. Results of investigations. On the basis of collected results of these experiments a statistical analysis was made for the purpose of finding the four functions $S = f(V)$ for the two initiators and for dusts of the two kinds: $d85$ and $d25$.

On the basis of empirical data it was established that the explosibility degree S tends toward two limit values one of which is zero when the content of volatile matter diminishes, the other being a certain upper limit when the content of volatile matter in coal rises. The approach to both these limits is in the nature of an asymptote.

The curve which fulfils these conditions is the equiaxial hyperbola. Employing the method of the least squares, equations for the above stated conditions of the investigations are determined.

For the $d85$ coal dust with the initiator 30mPII

$$S = \frac{60.0}{12.5 - V} + 84.0 \tag{3.1}$$

The equation (3.1) requires the preservation of the condition $V > 12.5$.

In Fig. 3.1 curve I corresponds to equation (3.1). The points corresponding to results of relevant experiments were not marked in this figure because it would have made the drawing unintelligible on account of the

fact that it contains another three curves corresponding to the remaining three equations.

The particularly prominent scatter of certain points is explained in the original publications.

Investigations on which this work is based were conducted in the course of a long time, at various seasons and, consequently, under varying atmospheric conditions. The last named factor caused changes in the humidity inside the experimental gallery and these, in their turn, have influenced the results to a certain extent.

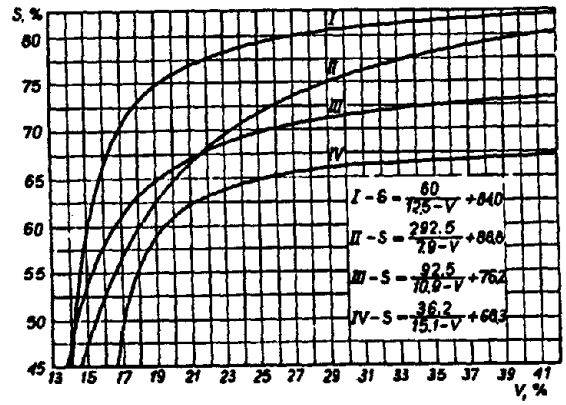


Fig. 3.1. Curves of the dependence of the coal dust explosibility S upon the content of volatile matter V: *I* — the *d*85 dust, initiator 30mPII; *II* — the *d*85 dust, initiator 50 cu m CH_4; *III* — the *d*25 dust, initiator 30mPII; *IV* — the *d*25 dust, initiator 50 cu m CH_4

The fineness of coal dust obviously exerts the fundamental influence upon its explosibility. In the experiments as the measure of this fineness the share d of fraction < 75 μm expressed in percentages is adopted. The grain composition of this fraction showed natural differences depending on the hardness of coal. This fact undoubtedly diminished the accuracy of the adopted measure of fineness. In experiments conducted on such a large scale the maintenance of constant conditions is very difficult which — naturally — has likewise adversely affected the accuracy of results.

For the *d*85 coal dust when the initiator used is 50 cu m CH_4

$$S = \frac{292.5}{7.9 - V} + 88.8 \qquad (3.2)$$

Equation (3.2) requires the fulfilment of the condition that $V > 7.9$.

In Fig. 3.1 curve *II* is presented which corresponds to the equation (3.2).

For the d25 coal dust when the initiator used is 30mPII

$$S = \frac{92.5}{10.9 - V} + 76.2 \qquad (3.3)$$

Equation (3.3) is conditioned by $V > 10.9$.

Curve *III* in Fig. 3.1 corresponds to the equation (3.3).

It should be noted that points marking the results of separate experiments show, as far as curve *III* is concerned, a wider scatter than the one observed in the preceding two groups of research operations. The maximum upward deviation from the regression curve amounts to 11 percent, and the downward deviation does not exceed 15 percent; yet the number of such points is small.

For the d25 coal dust the initiator used being 50 cu m CH_4

$$S = \frac{36.2}{15.1 - V} + 68.3 \qquad (3.4)$$

Equation (3.4) requires that $V > 15.1$.

Curve *IV* in Fig. 3.1 corresponds to the equation (3.4).

3.1.2.3. A general discussion of the function $S = f(V)$. The curves presented in Fig. 3.1 equalize the experimentally determined points sufficiently well.

Taken in their entirety the results show that instances of pronounced differences in the explosibility of coal dust, arising from the differences in the chemical properties of coals, are relatively rather infrequent.

Equations from (3.1) to (3.4) possess two asymptotes each. The values of horizontal asymptotes represent free terms. These values express the contents of incombustible solid matter which prevent a propagation of coal dust explosions even in the presence of the maximum possible content of volatile matter; in other words when the content of incombustible matter is equal to the free terms even the most explosive coal dust is safe as far as the propagation of an explosion is concerned. Of course this is true for the given degree of the fineness of the coal dust and for the given explosion initiator which correspond to the relevant equation.

The value of the perpendicular asymptote can be determined when it is assumed that $S = 0$. In this way one finds the limit content of volatile matter in the presence of which coal dust becomes already incapable of propagating an explosion under conditions corresponding to those for which the relevant equation is valid.

The values of V found with the aid of equations (3.1) to (3.4) correspond quite well to data obtained experimentally. Only in the case of the equation (3.2) the value of V is somewhat too low. When it comes to a general evaluation of the safety of coal dust on the basis of the content of volatile matter the most conclusive is equation (3.1) which refers to coal

dusts of the *d85* type and to a very strong initiator 30mPII. According to this equation the limit value of S amounts to about 12.5 percent which agrees very well with both Polish and foreign experimental data.

The curves *I*, *II*, *III* and *IV* in Fig. 3.1 give a comparative picture of the explosibility of coal dusts under four different conditions of investigations. Each of the curves illustrates the influence of volatile matter on the explosibility of coal dust under given conditions.

As regards all of the four curves up to between 18 and 20 percent of volatile matter the values of S grow very rapidly with the growth of the values of V. At higher V values the values of S increase more and more slowly so that the asymptote character of the curves becomes more manifest. For practical purposes it may be even assumed that coals containing more than 25 percent of volatile matter do not exhibit any differences in the explosibility of coal dust depending upon the growth of the content of volatile matter. The distances between the pertinent curves represent the measures of the differences in the explosibility of coal dusts.

The comparison between curves *I* and *II* and between curves *III* and *IV* illustrates quite well the influence of the initiator on the explosibility of coal dust. The distances between the curves in each of the two pairs show how much stronger is the initiator 30mPII than the initiator 50 cu m CH_4 and to what degree the difference between these initiators affects the difference in the explosibility of coal dusts.

The comparison between curves *I* and *III* and between curves *II* and *IV* gives a picture of the influence of the fineness of coal dust upon its explosibility when the same initiators are used. This influence is considered more closely in a separate chapter.

It is necessary to note that the functions discussed above refer to the explosibility of coal dust on a specified distance of 200 m of an experimental gallery. The dependence of the explosibility of coal dust upon the length of the zone under examination presents a very important problem which is to be discussed in Section 6.4.

3.1.3. The dependence of the coal dust explosibility index Z upon the content of volatile matter V

The results of investigations on the explosibility of coal dusts, discussed in Section 3.1.2, with reference to the four specified conditions may be expressed also in the form of the dependence of the index of coal dust explosibility upon the content of volatile matter: $Z = f(V)$.

Four curves are shown in Fig. 3.2 expressing functions $Z = f(V)$ with reference to the same conditions which were set in the case of functions $S = f(V)$.

The curves presented in Fig. 3.2 were plotted directly on the basis of the values of Z found in particular experiments under each of the series of the conditions of investigations, and not as the result of a calculated functional relation.

The differences between the curves give a comparative picture analogous to that resulting from the analysis of the curves presented in Fig. 3.1.

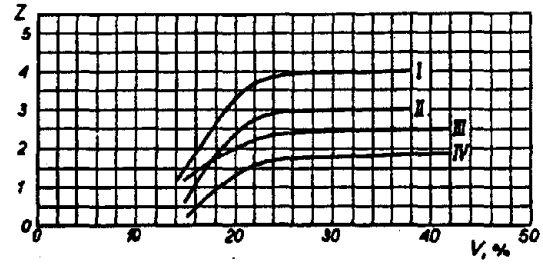


Fig. 3.2. Curves of the dependence of the coal dust explosibility index Z upon the content of volatile matter V: *I* — the *d*85 dust, initiator 30mPII; *II* — the *d*85 dust, initiator 50 cu m CH_4; *III* — the *d*25 dust, initiator 30mPII; *IV* — the *d*25 dust, initiator 50 cu m CH_4.

3.1.4. Comparison between the results of investigations on the explosibility of coal dust carried out in the *EM Barbara* and the results of such investigations carried out abroad

Investigations on the dependence of coal dust explosibility upon the contents of volatile matter were conducted in particular by: Taffanel in France [166], [167], Rice, Paul and Greenwald in America [138] and Mason and Wheeler in Great Britain [117].

Notwithstanding the fact that investigations on the dependence of the explosibility of coal dust upon the contents of volatile matter were carried out in France, as well as in USA and Great Britain under different conditions from those which existed in the *EM Barbara*, the presentation of all the results of these investigations in one diagram has a certain value as a means of comparing them.

Taffanel performed 19 experiments in a gallery of a circular cross section of 2.8 sq m and only 65 m long. The fineness of the coal dust had been of a higher degree than that of the dust in the *EM Barbara*. Taffanel used two kinds of initiators: the *limite 1* and *limite 2* both weaker than 30mPII and 50 cu m CH_4. The *limite 1* consisted of a 240 g charge of explosive gelatine and the *limite 2* — in addition to an identical charge — had a 10 m zone covered with pure coal dust similar to the *d*85 dust used in the *EM Barbara*. The graphic expression of the Taffanel's investigations (*Lièvin*) is given in Fig. 3.3 in which, at the same time, curves *I* and *II* are

shown representing the results obtained in the *EM Barbara* with the use of the initiator 30mPII and of the initiator 50 cu m CH_4. French results are given only for the initiator *limite 2*. As can be seen in Fig. 3.3 the explosibility of French coals, under conditions in which Taffanel's investigations were carried out, had been markedly lower than the explosibility of Polish coals particularly in the case of coals containing more than 18 percent of volatile matter.

It ought to be stated, however, that under the conditions of Taffanel's investigations the resulting denotations of the explosibility of the dust with low contents of volatile matter should be regarded as rather unreliable.

In the *EM Bruceton* (USA) 30 experiments were performed. The experimental gallery there had a rectangular shape. Its cross section was 6 sq m. Two explosion initiators were used: so-called *ignition test* corresponding to the Polish direct initiator and closely resembling the French *limite 1*, and the *propagation* test in which a 15 m zone of dangerous coal dust was initiated by a charge of 4 lb of black gunpowder. This last named initiator is weaker than 30mPII and approaching the 50 cu m CH_4 initiator.

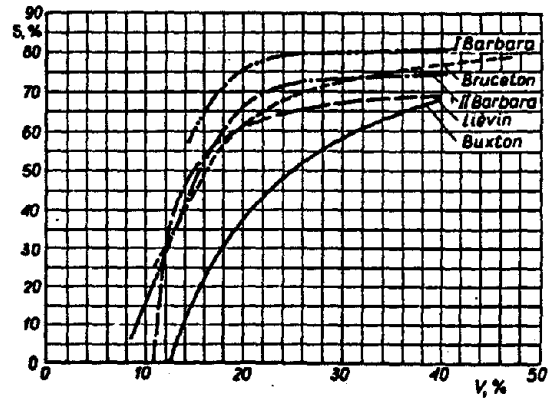


Fig. 3.3. Curves of the dependence of the explosibility of coal dust *S* upon the content of volatile matter *V*.

The fineness of the coal dust was similar to that of the dust used in the *EM Barbara*. The coal dust used in these investigations came from seams with the content of volatile matter from 6 to 49.7 percent. The results of American investigations are drawn as the *Bruceton* curve in Fig. 3.3.

Note that the results of American investigations come close to the results of investigations carried out in the *EM Barbara* with the use of the initiator 50 cu m CH_4 (curve *II*). It should be stated also that American tests were made in a 120 m gallery and this constitutes a difference

between the *Bruceton* and *Barbara* conditions. On the whole, however, one may consider the results of American investigations to be quite comparable with the results of Polish experiments taking into account the cross section and the length of the gallery, as well as the use of the initiator approximating the initiator 50 cu m CH_4.

British investigations (at *Buxton*) were carried out in an experimental surface gallery only 122 cm in diameter and 98 m in length. Twenty-two experiments were made in which coal dust from 11 seams was used containing from 12.2 to 37.4 percent of volatile matter. A charge of 560 g of gunpowder was used as the initiator. Consequently the initiator was very weak. The results of British investigations are also shown in Fig. 3.3. It is clearly seen that British investigations, carried out under the safest conditions, show the lowest explosibility of coal dust in comparison with the results of investigations carried out in other countries.

The arrangement of different coals in the order of their explosibility — as it appears in Fig. 3.3 — is obviously not to be regarded as strictly reliable since there were considerable differences between the conditions under which investigations were carried out in each of the relevant countries and, moreover, since the accuracy of the results — depending on the number of experiments made — varies considerably. The graphs in Fig. 3.3 represent merely the dependence of the explosibility of coal dust upon the contents of volatile matter under different experimental conditions.

At any rate it has been established generally that coal dust becomes incapable of propagating an explosion when it contains from 10 to 12 percent of volatile matter.

Normally the contents of volatile matter in the coal from a particular seam are determined by examining a classical test sample containing coal from the entire thickness of the seam. Investigations carried out in the *EM Barbara* proved [23] unexpectedly that the evaluation of the explosibility of coal dust on the basis of the content of volatile matter, determined through examining a sample collected in this manner, can be deceptive. Examining coal dust from a seam containing 11.5 percent of volatile matter ($V = 11.5\%$) it was found unexpectedly that this dust had been uncommonly capable of exploding. In the course of carrying out experiments with this coal a test explosion of its dust was performed in which the dust had a fineness of very high degree — that is, the specific surface $F = 8410$ (14,700) sq cm/g. The dust contained 28.4 percent of incombustible solid matter. The initiator used was 27.5 cu m CH_4. The explosion of the dust achieved the velocity of the order of magnitude of 2000 m/sec causing damages to the experimental gallery. The result of this kind was quite unexpected when $V = 11.5$ percent. This uncommon occurrence was due to the fact that the coal dust in the experiment actually contained 17.3 percent of

volatile matter or 5.8 percent more than the coal in the seam. The graph representing the velocities of the flame of this explosion is shown in Fig. 3.4.

This experiment indicated that there may occur considerable differences between the chemical composition of fine grains of dust and of coarser grains. The variability of this factor may act in a bidirectional

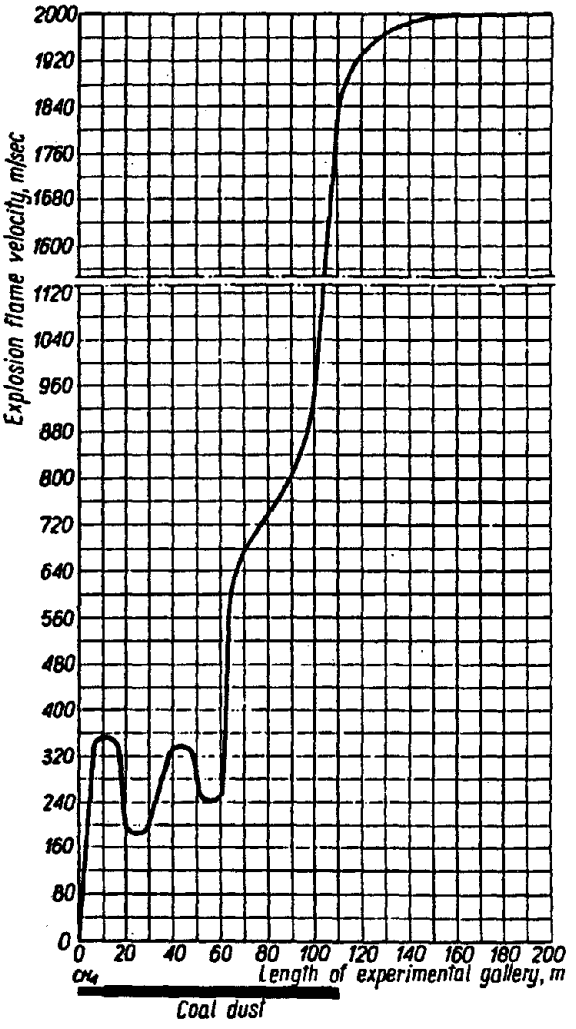


Fig. 3.4. A diagram of the coal dust explosion No. 680; seam 18V; the "powder" dust; F = 8410 (14,700) sq cm/g; V = 17.3%; n = 28.4%; the easiest dispersion conditions; initiator 27.5 cu m CH_4.

manner. Coal is not a homogeneous material and its components possess different physical and chemical properties. As the result of this, the

fineness of coal brings in effect a diversity of the chemical composition of particular fractions and the most pronounced differences — in comparison with the original substance — are likely to appear in the finest fractions in which the content of volatile matter varies as a general rule; naturally, in consequence of the above, differences in the explosive properties of the examined material are observed.

In the separate coal producing countries, in which investigations are conducted on the explosibility of coal dust, it is a common practice to use a certain standard coal for experimenting. Obviously it would be desirable to carry out investigations on the explosibility of these standard coals under uniform research conditions. This would be very important as a means of making the results obtained in separate countries comparable with each other. Unfortunately it has not been achieved on a large scale. The *EM Tremonia* (the Federal Republic of Germany) has been the only one to carry out such comparative investigations on standard coals from Poland, Great Britain and the Federal Republic of Germany. Particulars of the results of these investigations are not known to the author of the present book.

The investigators from the Federal Republic of Germany stated in general that these coals can be grouped as follows beginning from the most explosive in the descending order: the British, Polish and West German coals.

3.2. THE EFFECT OF THE FINENESS OF COAL DUST ON ITS EXPLOSIBILITY

3.2.1. The ways of determining the fineness of coal dust

The most common way of determining the fineness of dust is a sieve analysis. With the aid of this analysis the percentage content in the dust of particular grain fractions can be established.

The simplest method of determining the fineness of coal dust, employed in a considerable majority of investigations carried out in the *EM Barbara*, is the determination of the content in coal dust of that fraction which passes through a sieve of a 75 μm mesh. This content is denoted by the symbol d and is expressed in percentages.

The adoption by the *EM Barbara* of this very simplified method makes it possible not only in the *EM Barbara* but also in any mine laboratory to determine the fineness of coal dust by the mass performance of the described tests — that is, by carrying them out quickly with regard to numerous samples.

This method is analogous to the way of measuring the fineness of coal

dust adopted by the first investigators of the explosibility of coal dust, headed by Taffanel.

It is a noteworthy fact that this simple way of measuring the fineness of coal dust, when applied to dusts from different seams, does not produce major deviations from the average in the results of the examination of the explosibility of coal dust coming exactly from different seams. If such a simple way of determining the fineness of coal dust enables one to compare the explosibility of coal dust from different seams, the cause must consist in this that the grain composition of a coal dust, whose fractional value is lower than 75 μm, has to differ but very slightly in the majority of coal dusts originating from different seams. In order to verify this assumption 36 analyses were made of the grain composition of different coal dusts from other mines, and of the standard *Barbara* dusts *d*25 and *d*85 [161].

On the basis of these analyses the curves were plotted representing the grain-size composition shown in Fig. 3.5.

Attention is drawn to the fact that the grain-size composition of the dust < 75 μm for the *Barbara* dust *d*25 is relatively close to the mean values found for the 36 samples of dusts from other mines. The pertinent investigation results were statistically elaborated.

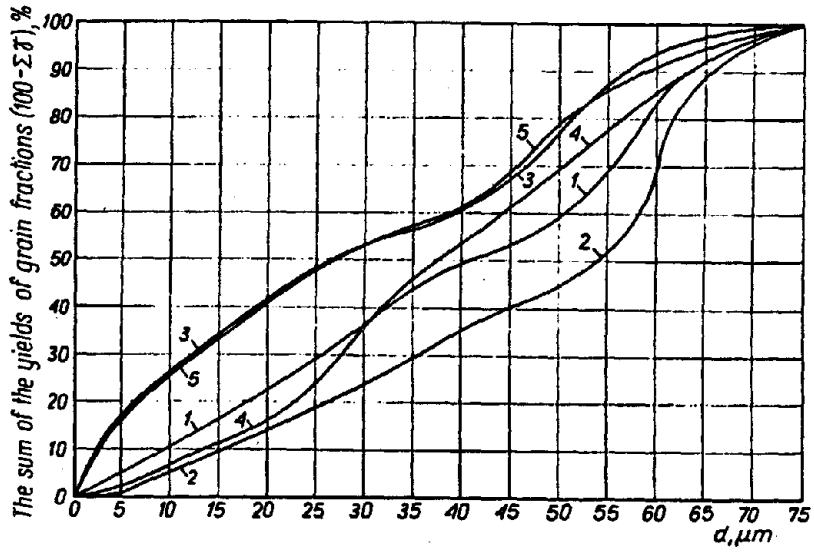


Fig. 3.5. A diagram of the grain size distribution of coal dust < 75 μm: *1* — the curve plotted on the basis of the mean values obtained from the examination of 36 mine dust samples; *2* — the curve plotted on the basis of the lowest values of the grain fractions found in the course of the examinations; *3* — the curve "maximum" representing the highest found values of the grain fractions; *4* — the curve representing the *d*25 *Barbara* coal dust; *5* — the curve representing the *d*85 *Barbara* coal dust.

The grain-size composition of the coal dust < 75 μm, shown in Fig. 3.5, has been determined with the aid of a sedimentation balance which makes it possible to find the percentage of the particular fractions contained in the sample of dust. This instrument registers the increments in the weights of the sedimentation factor per unit of time. The range of the grain sizes measured is from 1 to 60 μm.

A more detailed description of the percentage contents of the particular fractions of the dust, determined with the aid of the sedimentation balance, is given in the documentation of the *EM Barbara* [161].

As the most proper and relatively very simple way of measuring the fineness of dust one may consider the method of determining the dust's specific surface.

This method consists in measuring the velocity of the flow of air through an appropriately compressed layer of the dust when the difference between the pressure on both external sides of the cross section of the dust layer is known. In this way the geometric surface of the grains is measured since air does not pass through any fissures in the grains themselves. The method is applicable most advantageously to very fine dusts — that is, to those in which grains of a diameter not in excess of some three score μm prevail.

A direct measurement of the velocity of the flow is difficult because of its very low value.

The specific surface is calculated with the aid of an equation introduced by Kozeny and, quite independently, by Faiz and Hatch. This equation, modified by Carman is known in the form given below as the Kozeny-Carman equation

$$v_p = \frac{1}{K \cdot \mu \cdot S_v^2} \cdot \frac{\varepsilon^3}{(1-\varepsilon)^2} \cdot \frac{A \cdot \Delta p}{L} \tag{3.5}$$

where

v_p — velocity of the airflow,
K — the Carman constant,
μ — viscosity of the air,
S_v — the surface of the dust per unit volume,
ε — porosity of the layer,
A — the surface of the transverse cross section of the layer,
Δ_p — the difference between pressures acting upon the upper and upon the lower surfaces of the layer,
L — thickness of the layer of dust.

The Carman coefficient K is nondimensional and its value determined experimentally amounts to 5.

The instrument used for determining the specific surface of the dust is shown in Fig. 3.6.

The way in which measurements are made is described in the publication [161]. This method of measuring the specific surface of coal dust or of stone dust is employed in the *EM Barbara* in all investigations requiring a rather accurate determination of the fineness of the dust.

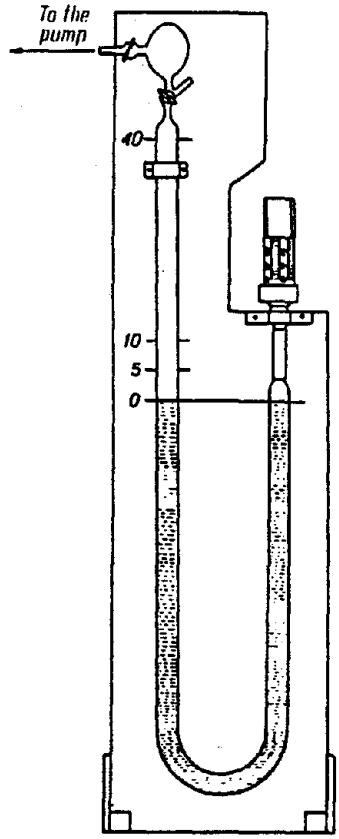


Fig. 3.6. The instrument for determining the specific surface of the dust (after Kamack).

By way of an example it may be stated that the commonly used *d*85 *Barbara* dust has, on the average, a specific surface of 3850 sq cm/g while the *d*25 *Barbara* dust has the average specific surface of 1750 sq cm/g.

Coal dusts from other mines corresponding to the *d*25 *Barbara* dust have specific surfaces varying from 3000 to 4400 sq cm/g. Coal dusts corresponding to the *d*85 *Barbara* dust have specific surfaces oscillating between 4000 and 10,000 sq cm/g.

The *d*25 coal dust of the brown coal from the *Sieniawa* mine has the specific surface of 1450 sq cm/g.

Likewise intersting are data concerning limestone dusts used for dusting mine workings or in stone dust barriers.

The specific surface of the limestone dust *Strzeblów* is about 2300 sq cm/g while that of the stearin treated limestone dust *Sosnowiec* varies from about 3000 to 3500 sq cm/g.

The method of denoting the value of *d*, employed since long ago in the *EM Barbara* permits of expressing the fineness of dust by a single number.

The median represents simply the diameter of a grain in relation to which 50 percent of the bulk of all grains of the given dust are of a smaller diameter, while the other 50 percent of these grains are of a larger diameter. This definition appeals very strongly to the imagination. The disadvantage of this method, however, consists in this that for finding the median one must make a very accurate sieve analysis of the dust with the aid of a sedimentation balance. In Fig. 3.7 an example is shown of the way of determining the value of the medians.

As can be seen from the diagram given in Fig. 3.7 the values of the median amount to: $M_1 = 26\ \mu m$; $M_2 = 37\ \mu m$; $M_3 = 35\ \mu m$; $M_4 = 33\ \mu m$.

The median can also be determined for normal coal dust — that is, for the dust passing through a sieve of 1 mm meshes.

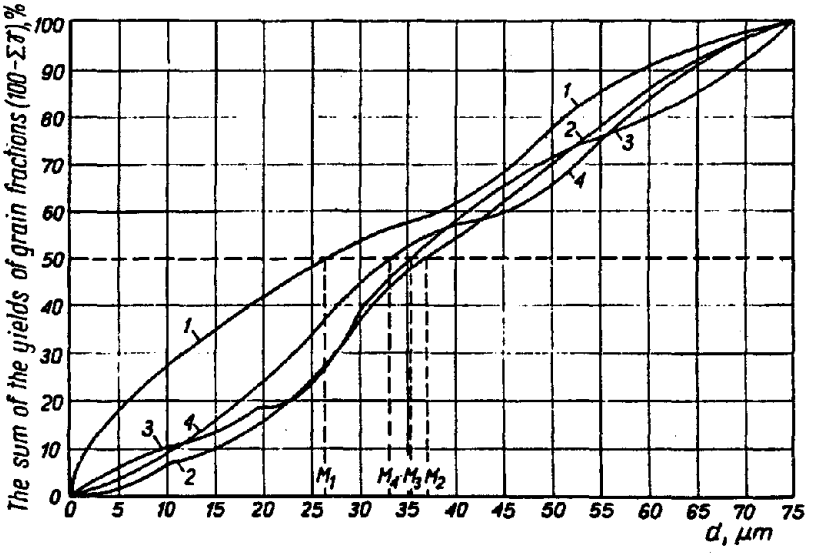


Fig. 3.7. An example of the way of determining the medians of the coal dust fractions $< 75\ \mu m$: *1* — for the d85 *Barbara* dust; *2* — for the d25 *Barbara* dust; *3* — for the *Barbara* dust obtained from the drillings in the upper bench; *4* — for the *Victoria* dust (seam 25).

A comparison of the three above described principal ways of measuring the fineness of coal dust in which the medians for dust fractions below 75 μm are also taken into account, is presented in Table 3.1.

3.2.2. The results of investigations on the dependence of the explosibility of coal dust upon its fineness

In the investigations described in this section as the measure of the fineness of coal dust is adopted its specific surface denoted hereafter by the symbol F and expressed in sq cm/g. The investigations in question were carried out in the *EM Barbara* in the years 1945 [21] and 1952 [23].

According to both Soviet [106] and American [92] investigations coal dust explosibility grows as the dust becomes finer up to a certain limit and then begins to decline. At any rate such views prevailed at the time

Table 3.1

A Comparison between the Fineness Parameters of Various Coal Dusts

Name of the dust	Content of fraction < 75 μm d %	Specific surface of the dust sq cm/g	The median value for dust < 1 mm	The median value for dust < 75 μm
Barbara *d*25 (from coal dust mill)	25	1750	340	38
Barbara *d*85 (from coal dust mill)	85	3850	38	28
Barbara, upper bench (drillings)	13.8	2180	320	36
Barbara, lower bench (drillings)	19.2	2100	305	46
Victoria, seam 25 (from the belt-conveyor point)	20.4	—	335	33
Sosnowiec, seam 510 level 280 m (from the winning operations)	16.8	344	340	47
Jaworzno, seam 302 level 500 m (from the winning operations)	17.9	508	313	51.2

when, in the *EM Barbara*, works were inaugurated to investigate this problem.

At that time for determining the percentages in the dust of fractions 0–2.5; 2.5–5; 5–10; 10–15; 15–20; 20–25; 25–30; 30–35; 35–40; 40–50; 50–60 μm the Andreason method and, for calculating the specific surface, the Rosin and Rammler method [147] were used.

Research operations for establishing the dependence of S upon d or F were carried out in an experimental gallery the cross section of which measured 5 sq cm and its length was 140 m. Coal dust from the seam 416 of the *Wujek* mine was used containing volatile matter $V = 36$ percent and hygroscopic water $W_h = 1.3$ percent.

As the initiator 25 cu m CH_4 was used ignited by a shot of 750 g of black powder.

Two separate series of researches were made:

— under the most favorable conditions of dispersion with coal dust placed on the roof bars,

— under the most difficult conditions of dispersion with coal dust placed on the floor of the gallery.

Experiments were made with five magnitudes of the fineness of coal dust. Clay-slate dust was used as stone dust.

The results of investigations on the dependence of coal dust explosibility, and of the index of the explosibility of the dust, upon its fineness are given in Table 3.2 and are presented in a graphic form in Figs. 3.8 and 3.9.

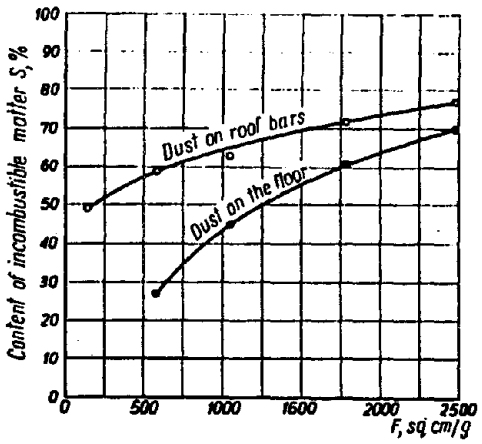


Fig. 3.8. The dependence of the coal dust explosibility S upon the specific surface F of the dust of coal from seam 416.

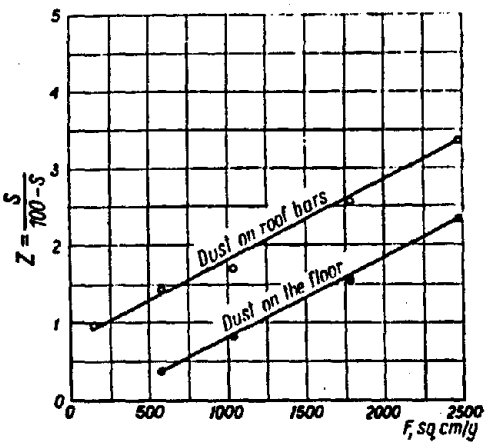


Fig. 3.9. The dependence of the coal dust explosibility index Z upon the specific surface F of the dust of coal from seam 416.

The dependence of Z upon F may be expressed by the following equations:

— assuming that dust grains are of a spherical shape:
for the most favorable dispersion conditions

$$Z = 0.0010119F + 0.7836578 \tag{3.6}$$

for the most difficult dispersion conditions

$$Z = 0.0010119F + 0.2445773 \tag{3.7}$$

— adopting the Heywood coefficient closely approaching the actual shape of the grains:
for the most favorable dispersion conditions

$$Z = 0.000578F + 0.7836578 \tag{3.8}$$

for the most difficult dispersion conditions

$$Z = 0.000578F + 0.2408665 \tag{3.9}$$

Table 3.2

Results of Investigations on the Dependence of the Explosibility of the Coal Dust from Seam 416 upon the Fineness of the Dust

Location of the dust	Specification of parameters	Content of fraction < 75 μm, %				
		85	50	25	12.5	2.8
		specific surface of coal dust F, sq cm/g				
		2480	1790	1040	580	140
On roof bars	S — explosibility of coal dust; contents of incombustible matter sufficient to prevent the propagation of an explosion, %	77	72	63	59	49
	p_1 — contents of incombustible matter in the fraction < 75 μm, %	67	72	75	82	90
	Z — explosibility index according to the author	3.35	2.57	1.8	1.44	0.96
	ratio of the surface of stone dust to the surface of coal dust in the mixture	3.00	2.98	3.11	4.42	11.90
On the floor	S — contents of incombustible matter sufficient to prevent the propagation of an explosion, %	70	61	45	27	14*
	p_1 — contents of incombustible matter in the fraction < 75 μm, %	60	61	60	52	24*
	Z — explosibility index according to the author	2.33	1.56	0.82	0.37	—
	I — explosibility index after Mason and Wheeler	3.33	2.56	1.82	1.37	—
	ratio of the surface of stone dust to the surface of coal dust in the mixture	1.99	1.69	1.28	0.75	—

*The d 2.8 dust placed on the floor did not propagate an explosion with natural content of incombustible matter $S = 14\%$ and $p_1 = 24\%$.

Investigation results described above prove that, contrary to the mentioned opinions of foreign investigators, the explosibility of coal dust grows as the dust becomes finer without reaching any maximum at all for a given fineness beyond which the explosibility had been thought to decline.

The ascertainment of the rectilinear dependence of the explosibility index Z of coal dust upon the degree of its fineness is of paramount importance and finds an application in the derivation of general formulas expressing the dependence of the explosibility of coal dust on the basic explosibility factors.

3.2.3. The fineness of the mine coal dust

Hereafter the mine coal dust will be called in short the mine dust.

On account of the great influence of the fineness of coal dust on the explosibility of coal dust it is necessary to know the degree of the fineness of the dust present in mine workings.

In the *EM Barbara* since years ago investigations are being carried out on the problem of the hazard of coal dust explosions in mines. With this end in view samples of coal dust characteristic of particular seams and workings are collected.

Note that these samples are not collected systematically from all mines and seams because the investigations in question are undertaken when the mining authorities, or a mine, express a wish to have a particular dust examined. Nevertheless the number of samples collected in particular periods of time is very large.

A comparative list of the results of investigations on the fineness of mine dusts, carried out on the samples collected in the separate periods of time, is very interesting. As previously explained the percentage of the fraction $< 75\ \mu m$ — that is, the magnitude d is adopted as the measure of fineness. It should be mentioned that during many years the percentage determined referred to the fraction $< 120\ \mu m$. In the period between the wars, in the years from 1925 to 1939, 677 samples of mine dust were collected. In the postwar period, between the year 1945 and February 22, 1949, 400 samples of coal dust were examined. In the period between January 1, 1965 and July 15, 1970 the number of coal dust samples examined amounted to 2442.

The results of the examination of the samples for the first mentioned two periods of time are given in the publication [21].

The results of the established fineness of the dust in the form of curves, representing the frequency of the occurrence of particular degrees

of fineness, are presented in a diagram in Fig. 3.10. From the graphs given in Fig. 3.10 it can be seen that in the years between 1925 and 1939 the most frequently occurring magnitude of d is contained between 15 and

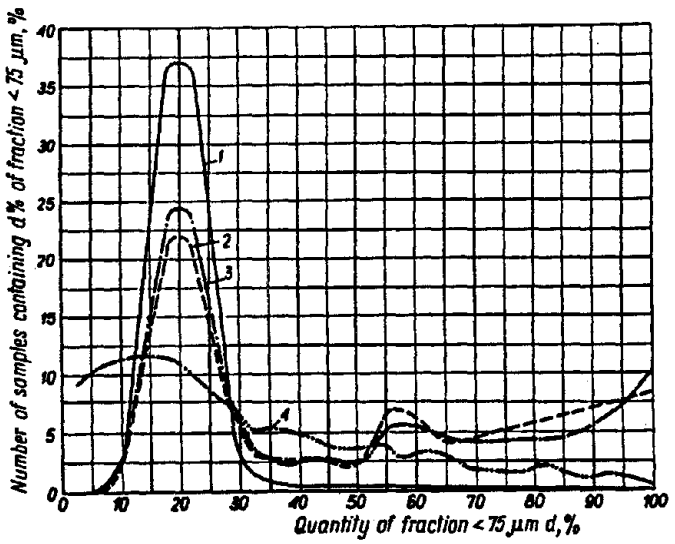


Fig. 3.10. Curves of the frequency of finding the fraction of coal dust fineness < 75 µm: *1* — samples collected from mines in the period from 1925 to 1939; *2* — samples collected from mines in the period from 1945 to Feb. 15, 1949; *3* — samples collected from mines in the period from 1945 to Feb. 15, 1949 exclusive of the Lower Silesian mines; *4* — samples collected from mines in the period from 1965 to July 15, 1970.

25 percent. A dust containing more than 30 percent of this fraction seldom occurred. In the first postwar period the magnitude of d frequently occuring also amounted to 15–25 percent but this type of dust was not as frequent as it had been in the period before the World War II. On the other hand much more frequent was the occurrence of the dust of a high degree of fineness. The curves which refer to these two periods of time are, indeed, not badly comparable at all, since the samples collected contained relatively small quantities of stone dust used to dust the workings according to regulations. Obviously the presence of stone dust obliterates the picture of the fineness of coal dust particularly when it is used in quantities approaching those demanded by regulations.

During the third period, in the years from 1965 to 1970, the samples were collected in workings which were intensively dusted with stone dust. For that reason the magnitude of the fineness of coal dust was fixed with reference to pure coal dust contained in every sample. Undoubtedly this fact had a certain influence on the comparability of the results of the

examination of samples during the third period with those of the former two periods. It should also be noted that in the third period samples were collected chiefly from the 200 m zones in which the dusting with stone dust was required by regulations, while in the two former periods such samples were collected from much longer parts of workings.

Considered generally the curve, which refers to the last of the three periods, shows a lower degree of fineness of the dust than that established with reference to the former two periods. This cannot describe truly the actual situation when the growth of the mechanization of mining operations is taken into account. Only as far as the contents of 30 to 50 percent of the fraction d are concerned the frequency of the occurrence of such dusts in samples, collected during the third period, is higher than the corresponding frequency in the former two periods. However, as was already pointed out, the curve from the last period cannot be regarded as adequately comparable with the curves representing previous periods.

The mechanization of mines and, particularly, the mechanization of the winning of coal causes undoubtedly a greater fineness of coal dust. Unfortunately there is no precise data concerning coal dust in mine exploitation (in Section 1.2 general information, about explosions of fine coal and coal dust, was given).

It is necessary to say that the dustiness of workings can be diminished very effectively through injections of water into seams, and through spraying with water of all the places close to mechanical installations producing coal dust and of the transfer and discharge points.

A very important factor in combating the dustiness of workings is the consolidation of coal dust on their floors.

The influence of the fineness of coal dust on its explosibility is actually even more pronounced than described in this section. It should be emphasized that the effect of the fineness of coal dust on its explosibility has been considered here under conditions created by the use of a strong initiator. However, with the growth of the degree of the fineness of coal dust, grows very markedly also its dispersibility which is a phenomenon to be observed clearly only when varying initiators are used.

While these factors will be discussed later on in this book it is advisable to have them mentioned here because the parameters of the fineness and dispersibility of coal dust, of the strength of the initiators and of dispersion conditions are strictly connected with each other. Without taking note of the above the mere notion of the influence of the degree of fineness upon the explosibility of coal dust would not have been complete.

It should be noted also that the fineness of coal dust in a single working is not uniform. As a rule the finest are the surface layers of dust de-

posits. These layers, very thin indeed (their thickness is expressed in micrometers), play a tremendous part in coal dust explosions. This problem was dealt with in the *EM Barbara* and will be discussed in Section 6.1. In fundamental investigations, however, it was necessary to make use of coal dust mixtures of a uniform degree of fineness.

In particular workings the fineness of coal dust shows considerable differences, for example, as a rule the highest degree of fineness is observed in belt-conveyor roads, especially in the vicinity of transfer and discharge points. This is why the mining authorities are forced to base the requirements contained in the binding regulations, concerning safety in mines, upon the assumption that the degree of the fineness of coal dust exceeds its average fineness. Polish regulations are based, in principle, on the $d85$ coal dust.

Other countries have adopted a very similar fineness of coal dust which must be protected according to binding regulations against the propagation of explosions.

3.3. THE EFFECT OF THE CONTENT OF INCOMBUSTIBLE SOLID MATTER ON THE EXPLOSIBILITY OF COAL DUST

3.3.1. General information

The influence exerted by the content of incombustible solid matter on the explosibility of coal dust was discussed already in Section 2.1.1 in connection with the problem of determining the degree of the explosibility of coal dust.

To incombustible solid matter in the mine dust the following is counted:

— hygroscopic water W_h,

— incombustible solid matter contained in coal extracted from the seam, the so-called ash p,

— incombustible matter originating from crushed roof and floor rocks,

— limestone dust (or other kinds of stone dust) added to the mine dust in accordance with regulation requirements.

Hereafter in this book the content of incombustible solid matter in the mine dust will be denoted generally by the symbol n. The content of such matter sufficient to make the dust incapable of propagating explosions will be denoted by the symbol S as was stated already in Section 2.1.1. In the mine dust, without the addition of limestone dust, there is usually more incombustible solid matter than the quantity of ash contained in coal extracted from its seam.

In principle the role of incombustible solid matter in preventing the development of coal dust explosions appears to be extremely simple. It is known from everyday practice that an increase in the quantity of stone contained in coals makes the burning of the coals more difficult since the heat of the combustion of coal is used up in a great measure for warming stones. Likewise, in the case of a cloud of coal dust containing stone dust a part of the heat, produced by the combustion of coal dust, is transmitted to solid incombustible matter and this, naturally, makes the development of the flame in the cloud of coal dust more difficult.

But the most important role played by incombustible solid matter in a cloud of coal dust consists in this that particles of the incombustible solid matter shield the particles of coal dust, serving as screens, from the radiation of the light produced by the reaction of the combustion of volatile matter and residues of coke. As is known the heat energy is transmitted in the quickest and easiest manner through radiation. And it is exactly this form of the transmission of the heat energy that plays the dominating role in coal dust explosion. It is obvious that particles of incombustible solid matter in a cloud, consisting of a mixture of the coal and stone dust, screen the particles of the coal dust from the effects of this radiation. How big is the role of radiation in the process of a coal dust explosion is evident from the fact that, to make coal dust incapable of propagating explosions, very high contents of incombustible solid matter are needed exceeding even 80 percent. It is a characteristic feature that coal dusts containing very large quantities of incombustible solid matter, quite close to the value of S, are still able to propagate an explosion with a very strong effect in the form of a high pressure and a high velocity of the flame. At the same time it is known from everyday experience that coal containing, for example, 70 percent of stone (not to mention higher proportions) is practically useless — that is, it cannot be used to produce heat energy for household purposes. The example taken from the household practice is given here for the sole purpose of producing an easy picture of the phenomenon under discussion but, of course, everybody knows that in the industry coals cannot be used when they contain stone in such large quantities

One should not omit still another role played by stone dust in the prevention of the development of flame: stone dust makes difficult the diffusion of oxygen to the burning particles of stone dust obstructing, at the same time, the diffusion of combustible gases from the particles of coal dust. Thus stone dust obstructs the formation of explosive systems.

With reference to explanations given in Section 2.3.2.3 it should be stated that the ability of propagating explosions in a cloud, with very high content of incombustible matter, for example, close to 80 percent, is due to

a strong turbulent movement within the cloud of dust which causes a very rapid change in the position of the flame in relation to the dispersed particles of the coal dust and of the stone dust in the cloud. Because of this fact uncommonly high contents of incombustible solid matter in coal dust are needed in order to make it incapable of propagating explosions. These considerations make it obvious that the effectiveness of incombustible solid matter in obstructing the development of coal dust explosions depends, in a large measure, upon the degree of fineness of incombustible solid matter in other words upon the kind of limestone dust used. Here a very interesting fact is observed: the effectiveness in question increases to a certain limit degree of fineness beyond which the rate of this increment becomes relatively low. This problem has not been adequately elucidated. Nevertheless it is a fact that with the increase of the content in the stone dust of particularly small fractions, namely, < 10 µm the cohesion of the stone dust becomes stronger and the dispersion of the dust in air is made difficult. For this reason limestone dust used in coal mines ought not contain too large quantities of the fraction < 10 µm. The corresponding requirements are included in the binding standard.

3.3.2. Comparison of the effectiveness of various stone dusts

As a means of combating the explosibility of coal dust the dusting of workings with stone dust is applied on a large scale in all countries since long ago. Recently in the Federal Republic of Germany dust-absorbing pastes are used for this purpose. This last development will be dicussed in Section 8.8.

The most frequently used are limestone and clay-slate dusts and not so frequently the dusts of dolomite and gypsum and even the diatomite. Apart from being used for dusting the workings stone dusts are utilized on a large scale for barriers serving to check explosions. In view of the possibility that differences in the effectiveness of various kinds of stone dusts might play a serious role comparative investigations were made on their effectiveness.

The clay-slate dust contained in a cloud together with coal dust does not undergo any serious chemical changes during the development of the explosion flame. On the other hand, limestone dust may be decomposed under such conditions into carbon dioxide and calcium oxide.

The decomposition of calcium carbonate, occurring at temperatures above 800°C, is an endothermic reaction and, therefore, it causes the absorption of heat during an explosion. Moreover, the carbon dioxide educed in the course of this reaction when it amounts to 44 percent by weight may act as a strong restraining factor on the development of the flame being a nonflammable gas, naturally if the quantity of the evolved

carbon dioxide were sufficiently high. Thus, a foundation existed for a supposition that limestone dust might prove to be more effective than clay-slate dust.

British investigators [118], [119] carried out research work for determining the effectiveness of the limestone, clay-slate and other stone dusts. They established the existence of considerable differences between the effectiveness of various stone dusts. Tests were carried out in a surface gallery 100 m long, 1.22 m in diameter.

It was found that, with reference to a specified coal dust containing volatile matter $V = 33.3$ percent, the following limit percentages of various stone dusts were needed to make this type of coal dust incapable of propagating explosions:

slate	67.5
diatomite	62.5
anhydrite	60.0
limestone	57.5
dolomite	57.5
gypsum	40.0

The degree of fineness of the examined stone dusts had been close to being uniform since they contained about 85 percent of the fraction < 75 μm.

In their further investigations [100] the British research workers found that in order to make a slightly different coal dust, containing volatile matter $V = 36.5$ percent, incapable of propagating explosions 60 percent of limestone dust and 57.5 percent of dolomite dust were sufficient quantities.

Should the results of these British investigations be confirmed it would be possible, by using limestone dust instead of clay-slate dust, to reduce very considerably the quantity of the latter used in mine workings; according to these investigations for every kg of coal dust 2.08 kg of clay-slate dust are needed but only 1.35 kg of limestone dust.

Much more extensive investigations were carried out in the *EM Barbara* in a 100 m surface experimental gallery and in a 200 m experimental gallery in which tests of effectiveness of the limestone, shale and dolomite dusts were made. Five kinds of initiators were used in these investigations. A total of 492 experiments on a large scale were made [27].

Stone dusts used in these investigations had the following fineness and specific surfaces F:

— limestone dust $d65$ $F = 2150$ (3750) sq cm/g,
— clay-slate dust $d49$ $F = 2350$ (4100) sq cm/g,
— dolomite dust $d78.8$ $F = 1800$ (3150) sq cm/g.

The values of F given above were calculated on the assumption of the

spherical shape of the grains of dust. The values of F given in brackets were arrived at after taking into account coefficients which are thought to correspond to the real shape of the grains of dust. As it can be seen from the above schedule the stone dusts examined differed considerably from each other in respect of their fineness and, to a less extent, in respect of the values of F.

A total of 14 series of comparative tests of the effectiveness of the above named stone dusts were made.

The results obtained with reference to particular stone dusts may be summarized as follows:

— the results of five series of tests were identical in respect of the effectiveness of clay-slate dusts and limestone dusts,

— in the outcome of three series of tests clay-slate dusts showed to be slightly more effective than limestone dusts,

— in the outcome of three series of tests limestone dusts showed to be slightly more effective than clay-slate dusts,

— the results of two series of tests were identical in respect of the effectiveness of dolomite, limestone and clay-slate dusts,

— in the outcome of one series of tests the effectiveness of dolomite dusts has been found to be lower than that of clay-slate dusts.

Whenever differences were disclosed they did not exceed 2.5 percent.

Depending upon the conditions under which tests were made — that is, upon the initiator, the fineness of the coal dust and conditions of its dispersion the values found for S oscillated between 40.0 and 82.5 percent. The lowest value of S was obtained when direct initiator had been used (the firing of a charge of 750 g of gunpowder in the hole of a mortar) under difficult dispersion conditions and the coal dust being of the $d25$ type. The highest values of S, amounting to 82.5 percent, were established when the initiator used had been 15mPII under the most favorable dispersion conditions and with the use of $d85$ coal dust.

Under these very varied conditions it has been established that the examined stone dusts: the clay-slate dust, limestone dust and also dolomite dust are equally effective as a means of preventing the danger of the propagation of explosions.

Examination of the effects of the decomposition of limestone dust during explosions of coal dust, and estimates made on the basis of the results of these examinations of the quantities of the absorbed heat and of the quantities of the carbon dioxide produced, led to the conclusion that no experimental foundation existed to consider limestone dust as more effective than clay-slate dust [27].

Comparative investigations were also carried out on the problem of

the effectiveness of limestone and clay-slate dusts when used on barriers [26]. These investigations proved that the two dusts were equivalent.

In consequence of what has been said it is possible to claim that limestone and clay-slate dusts are equipollent in respect of their effectiveness in combating the dangers of coal dust explosions. Limestone dusts have other advantages which will be discussed in the chapter on the ways of preventing the danger of coal dust explosions. But as far as their higher effectiveness is concerned the results of British investigations — mentioned heretofore — were not confirmed. American investigations also failed to confirm the results of British investigations.

In the *EM Barbara* no tests were made with gypsum dust because this dust is never used in mines on account of its property of lumping. Waterproof stone dust, which is used in practice, will be discussed in the chapter on preventing the danger of coal dust explosions.

Attention is drawn to the fact that the results presented above do not contain any information on the effect of the fineness of stone dusts (within the limits characteristic of the particular kinds) upon their effectiveness. Neither did American investigators [139] establish — within a sufficiently broad range — the influence of the degree of fineness of stone dusts upon their effectiveness.

3.4. THE EFFECT OF THE CONTENT OF FREE WATER W_k ON THE EXPLOSIBILITY OF COAL DUST S

3.4.1. General information

Coal dust deposited in mine workings usually contains free water. The content of this water is a very important parameter of the explosibility of coal dust.

In Polish mines the humidity of the mine dust is often quite considerable. For this reason in the *EM Barbara* many experiments were made in order to determine the influence of free water upon the explosibility of coal dust [33].

It should be emphasized that in this chapter we are discussing free water, called also water in short, which should be discerned from hygroscopic water. The last named water, as was mentioned already, is treated as belonging to the incombustible solid matter. Only when the content of hygroscopic water is exceptionally high it might play a somewhat more serious role than that played by the mineral incombustible matter. Normally however, as was proved by investigations carried out in the *EM Barbara*, the inclusion of hygroscopic water in the general category of incombustible solid matter does not diminish the accuracy of the evaluation of

the effectiveness of incombustible solid matter in preventing the propagation of explosions.

Free water has a double effect as a factor lowering the explosibility of coal dust.

The way in which free water acts in lowering the explosibility of coal dust is entirely different from that of stone dust. This water, when contained in the mine dust in sufficient quantities, diminishes the dispersibility of the dust and makes more difficult the raising of the dust to the air and its dispersion in the air in the shape of a cloud. When the content of water is sufficiently high it prevents altogether the formation of an explosive system.

A very important role in the phenomenon discussed here is played by the initiator of the explosion. The *strength of the initiator* is a notion which included both the energy of the blast and the quantity of the heat energy produced by it.

With the increase in the energy of the blast produced by the initiator its capability of dispersing deposits of coal dust grows also. Apart from this a great role is played by the amount of heat produced by the initiator and the extent of its effect on the dust since the flame of the initiator, in proportion to the amount of its heat energy, vaporizes various quantities of water contained in the dust.

It is impossible to ignite coal dust by using a rather weak initiator while the same coal dust, when a very strong initiator is used, can produce an extremely violent explosion.

In addition to lowering the degree of dispersibility of coal dust water takes away the heat from the flame on account of its very high specific heat and of the high heat of evaporation (the specific heat of limestone dust is 0.203 cal/g while that of water is 1 cal/g, and the evaporation heat of water is as high as 538.7 cal/g).

3.4.2. The dispersibility of coal dust

3.4.2.1. General information. There is no precise method of determining the dispersibility of mine dust especially when it contains certain quantities of water. Rather primitive methods are in common use of a qualitative character only.

As a weakly dispersible dust is considered the dust which is incapable of being raised to the air by an ordinary method of blowing on it with the mouth and which — on being squeezed in the hand — leaves on the hand noticeable traces of humidity and, when the hand is opened, the squeezed dust retains the shape of the squeeze. The content of free water sufficient

to deprive the dust of its dispersibility, according to the definition given above, is denoted by the symbol W_L. The definition given above is obviously primitive and it is certainly necessary to work out an instrument that would permit to express the notion of dispersibility in more precise terms. Though attempts were made in Poland and abroad to determine the criterion of the dispersibility of coal dust in homogeneous mixtures with water by fixing the velocity of the air current at which coal dust undergoes a denudation — yet these attempts produced no sufficiently satisfactory results.

The value of W_L depends manifestly upon the degree of fineness of the coal dust. In the *EM Barbara* investigations were carried out on the dependence of W_L upon d — that is, upon the content of the fraction < 75 μm as well as upon the specific surface of the dust F. The results of these experiments, in which coal dust from the *Barbara* seam was used, are shown in Fig. 3.11. It is necessary to stress the fact that the graphs presented in Fig. 3.11 correspond to the average Upper Silesian coal. However, coals from certain seams differ considerably from the average coal because they contain large quantities of free water and, in spite of this, retain a high degree of dispersibility. The above applies in particular to younger coals, for example, to coals from seams of the 100 group.

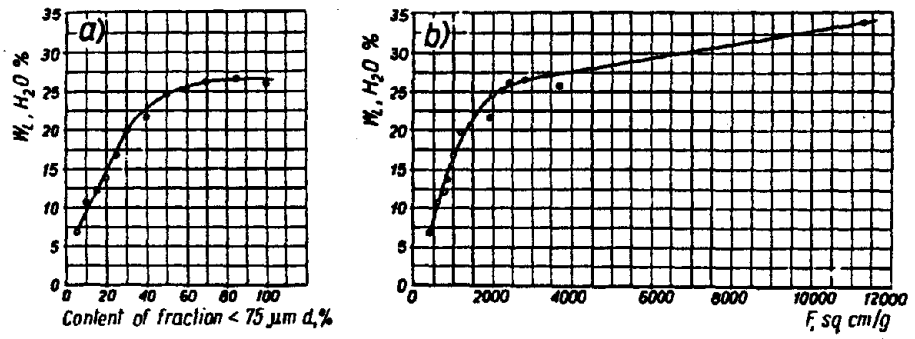


Fig. 3.11. The dependence of the content of free water W_L in the *Barbara* coal dust sufficient to deprive the dust of its dispersibility: a — upon the content of fraction $d < 75$ μm; b — upon the specific surface F of this dust.

The most classical example of coals which produce a dispersible dust, in spite of containing large quantities of free water, is provided by brown coals, particularly by lignites. The explosibility of the dust of such coals will be discussed in a separate chapter as these coals are markedly different from bituminuous coals.

3.4.2.2. Raising of dust by turbulent air currents [72]–[74]. Research work on this problem was conducted by Dawes and Wynn in the 'fifties at

the SMRE (Safety of Mines Research Establishment). In his very extensive and penetrating investigations Dawes demonstrated that there are two ways in which dust can be raised: the way of erosion in which single grains are raised from the surface of a deposit, and the way of denudation in which large agglomerations of the dust are torn away from the deposit and become dispersed in the air.

The factor deciding which of the ways will occur is the magnitude $\frac{\varrho^2}{C}$ where ϱ denotes the specific gravity of the dust (g/cu cm), and C denotes the cohesion (dynes/sq cm).

Cohesion is the force with which grains cohere, measured as the force necessary to tear a layer of dust per sq cm of the tear surface.

The stronger is the cohesion the more difficult is the raising of the dust. According to Dawes' experiment when $\frac{\varrho^2}{C} \geqslant 6$ erosion will occur.

An erosion of the deposit is a phenomenon less complicated than a denudation and it can be described in mathematical terms. The quantity of the dust raised Q (kg) within a period of time t (sec) amounts to

$$Q = K \cdot A \cdot V_0^3 \cdot \frac{\varrho^2}{C} t \tag{3.10}$$

where

K — a constant,
A — the total surface of the deposit, sq cm,
$V_0 = V - V_g$,
and here
V — the velocity of the air, m/sec,
V_g — the limit velocity of the erosion, m/sec.

Dawes estimates that a cloud of coal dust will be raised when the velocity of the air amounts to 5 m/sec, while a cloud of stone dust will need the velocity of the air to be 8 m/sec.

The phenomenon of denudation occurs chiefly in the case of a humid dust. The denudation is facilitated when the foundation is rough and it grows when the foundation vibrates. The actual conditions in mine roadways correspond to the conditions described above because the deposits of dusts are disturbed by the movements of men and machines. Also the shape of the deposit affects the process of denudation: if this shape happens to be streamlined the denudation is less probable. A deposit on a shelf in the central part of an aerodynamic tunnel (or roadway) will be raised by a denudation process more easily than a deposit on the floor of a roadway.

Deposits of a very high humidity (even such that form a mud) can

also be raised in the way of denudation. Consequently, explosions can be propagated in spite of a considerable humidity of coal dust.

3.4.3. The explosibility of wet mine dusts

As many as 428 experiments on a large scale were made in order to investigate the explosibility of wet mine dusts. The following kinds of coal dust were used in these experiments:

— *Barbara* d25	$F =$ 1120 (1960) sq cm/g
— *Barbara* d85	$F =$ 2800 (4900) sq cm/g
— *Barbara* powder	$F =$ 11,200 (19,600) sq cm/g
— the M708 seam d25	$F =$ 1190 (2080) sq cm/g
— the M708 seam d85	$F =$ 3680 (6440) sq cm/g
— the A713 seam d25	$F =$ 1170 (2050) sq cm/g

The limestone dust used in the experiments in question had the value of $d = 55.3$ percent, and the clay-slate dust — $d = 58.5$ percent.

The initiators used in the *EM Barbara* were those recognized as standard ones on account of the fact that they were employed in numerous series of investigations. These initiators represent a great variety in respect of their ability to initiate an explosion.

More particulars about the standard initiators described below are given in the publication [24].

In the experiments discussed here the following standard explosion initiators were used:

The direct initiator consisting of a charge of 750 g of gunpowder in the hole of a mortar. In front of the hole of the mortar a platform had been placed on which 2 kg of the examined dust was deposited. The zone with the examined dust had its beginning touching directly the mortar. Thus, the explosion of the examined dust was initiated directly by shot of the gunpowder. The direct initiator was very mild in respect of both the blast and the ignition of the dust.

The fact that the zone with the examined dust — to which as a common practice stone dust was added — touched directly the mortar made the initiation of an explosion very difficult because the primary cloud of the dust did already contain, as a rule, large quantities of incombustible matter. In consequence of this the heat of the combustion and the speed of the burning up of the primary cloud were lower than they would have been if, in the vicinity of the mortar, a pure dust were placed.

The 4 m initiator of pure dust in the amount of 0.5 kg/cu m differing from the former in this that the zone with the examined dust began at a distance of 4 m from the mortar. This arrangement fulfilled the regula-

tion requirements. The gallery sector of 4 m between the mortar and the zone with the examined dust was covered with pure coal dust of the degree of fineness corresponding to that of the examined dust.

The initiator now dicussed was denoted by the symbol 4mPI when the 4 m section was covered by the *d*25 dust likewise denoted by the symbol I.

When on the 4 m sector the *d*85 dust was used, denoted by the symbol II, the initiator we are discussing was denoted by the symbol 4mPII.

The introduction of the denotations of the *d*25 dust by the symbol I and of the *d*85 dust by the symbol II had been due to conditions connected with the preparation of these dusts and served also to simplify the symbols denoting the initiators.

The initiator 15mPII was characterized by the introduction of a 15 m zone covered by pure coal dust II. The quantity of this dust amounted to 0.5 kg/cu m. The distribution of the coal dust had always been the most favorable for its dispersion. This initiator is very strong. In practice it corresponds to short zones with dangerous dust not dusted with stone dust either because of an error, or because the fulfilment of regulation requirements had not been possible on account of the formation or deposition in the zone of very large quantities of coal dust. Such zones, unfortunately, are encountered in mines over distances much longer than 15 m.

The initiator 30mPII entirely analogous to the initiator 15mPII. The difference consists in the length of the zone covered with dangerous pure coal dust which, in this instance, amounts to 30 m. This initiator is obviously even stronger than the initiator 15mPII; actually this was the strongest initiator used in the basic investigations.

The initiator 50 cu m CH_4, consisting in this that 50 cu m of an explosive mixture of methane and air containing 8 to 9.5 percent of CH_4 is used. The ignition of this mixture was effected by firing a shot of 750 g of gunpowder from a mortar in the manner analogous to that applied in the case of all other initiators described here. This initiator is very strong though weaker than the initiator 30mPII.

Apart from the above mentioned initiators an initiator 27.5 cu m CH_4 was also used.

All investigations were carried out in a gallery 200 m long the cross section of which measured 5 sq m. The extension of these investigations to a gallery 400 m long was thought to be too risky because explosions of wet coal dust developed so violently that, undoubtedly, they would have caused far-reaching damages to a 400 m gallery. In the 200 m gallery the damages had been already quite serious.

For a rather long period of time it was thought that coal dust containing the quantities of water illustrated in Fig. 3.11 is sufficiently safe as far as the propagation of explosions is concerned.

According to regulations coal dust is regarded to be safe which being squeezed in the hand retains more or less the shape of the squeeze after the opening of the hand and leaves on the palm clear wet marks (Section 3.4.2). Investigations carried out in the *EM Barbara*, discussed in the present chapter, negated decidedly the above definition of a safe dust.

It was established that, depending on the strength of the initiator, the hazard of an explosion will change in what might be termed as a discontinuous manner. It was found that even a completely wet coal dust can propagate an explosion with a tremendous violence at that, if only the initiator of the explosion is sufficiently strong. In connection with this clear extremes occur.

When the initiators are weak relatively low contents of water, just corresponding to the graphs given in Fig. 3.11, make the dust incapable of propagating explosions so much so in fact that the coal dust in question does not even get ignited at all. Initiators of this kind occur when shots of small explosive charges are fired or when a local firedamp accumulation becomes ignited.

On the other hand a completely wet coal dust, containing water considerably in excess of its absorbing power, can be induced to explode exteremely violently when the explosion is initiated by a high accumula-

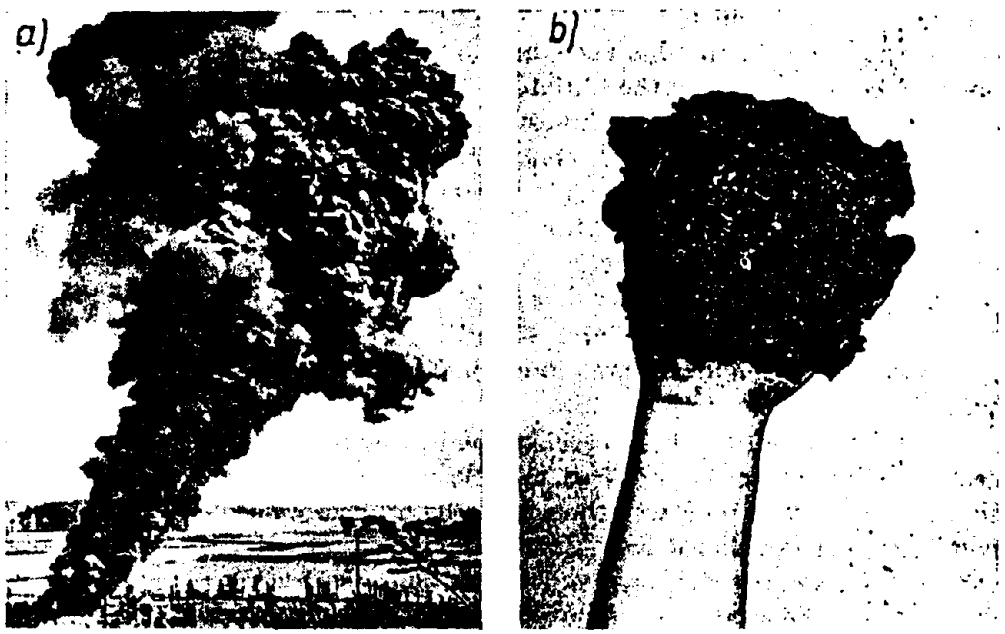


Fig. 3.12. Explosion No. 3574: the *d*85 dust, $W_k = 37.3\%$; *a* — a photograph of the explosion; *b* — the look of the *d*85 *Barbara* dust containing $W_k = 37.3\%$ used in the explosion No. 3574.

tion of a methane mixture or by an explosion in the zone of the dry dust. As an illustration of an explosion of this kind one can refer to Fig. 3.12*a* which gives a photograph of the ejection of the explosion No. 3574 of the *d*85 *Barbara* coal dust containing 37.3 percent of free water. What this dust looks like, when held in the palm of the hand, is shown in Fig. 3.12*b*. It is a mass of coal dust entirely saturated with water which oozes out of it.

The high explosibility of very wet coal dust is illustrated also by the graphs shown in Fig. 3.13*a*, *b*, *c*.

The graph in Fig. 3.13*b* gives an example of a situation in which, despite the contents of incombustible solid matter $n = 50$ percent, even as much as approximately 20 percent of free water proved to be inadequate as a protection against the propagation of the explosion which was very violent. The explosion graphically described in Fig. 3.13c was even more violent than one presented in Fig. 3.13*b*; the velocity of its flame reached 900 m/sec at the end of the gallery.

Note that in all instances, illustrated by Fig. 3.13, very strong explosion initiators had been used. All of the examples given were obtained under the most favorable dispersion conditions of the dust which had been placed on roof bars. It must be emphasized also that in all the instances discussed here coal dust used formed a uniform mixture with water.

An initiator weaker than the initiators used in the presented explosions can also cause a violent explosion of a humid dust in the complete absence of firedamp and of dry coal dust. This can occur when a rather big charge of an explosive is fired.

The initiator consisting exclusively in the firing of a shot of an explosive charge alone is called the direct initiator. If, along with a charge of 750 g of gunpowder which ignites coal dust, a charge of 1000 g of a permitted explosive is fired simultaneously, which does not ignite coal dust yet helps the gunpowder shot to raise coal dust, it would be possible to initiate a coal dust explosion when this dust is safeguarded partly by stone dust and partly by water (Fig. 3.14). It follows that even the firing of a shot of a big charge of an explosive can initiate an explosion of a humid dust provided that the explosive can ignite coal dust in question.

All of the examples given above are but an introduction to the problem of the explosibility of wet coal dust. The problem of the use of water as a protection against coal dust propagating an explosion has to be discussed thoroughly and very objectively. It is true that water is our great ally in combating the explosibility of coal dust and plays a very important part in the problem connected with it. Nevertheless, one should not turn back uncritically to the views prevailing some fifty years ago when

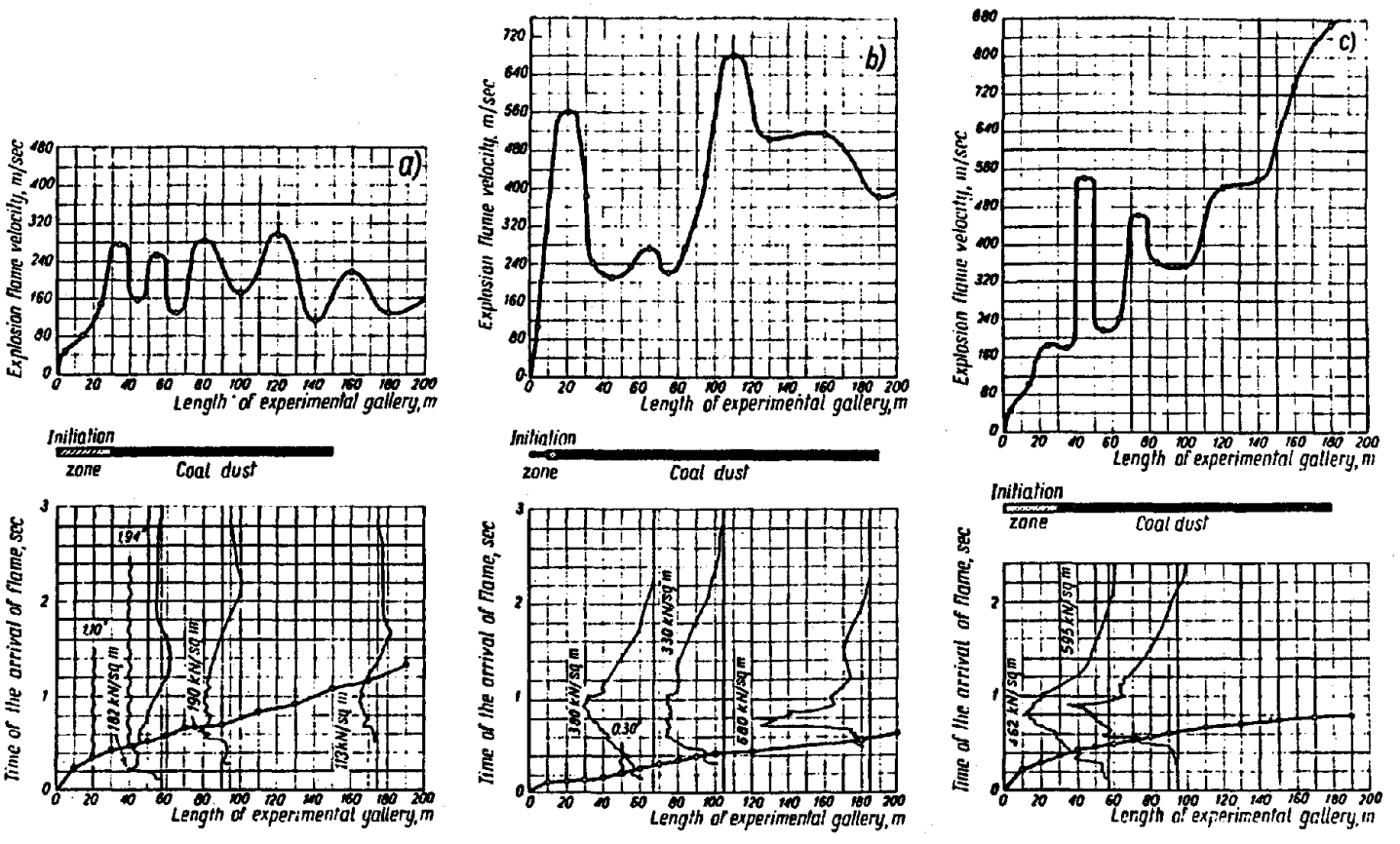


Fig. 3.13. Diagrams of explosions: a — No. 3533: the d85 *Barbara* coal dust, $n = 14.9\%$, $n_p = 9.2\%$, $W_k = 45.3\%$, $q = 0.5$ kg/cu m, initiator 30mPII, the easiest dispersion conditions; b — No. 1784: the d85 *Barbara* coal dust, $n = 50\%$, $n_p = 40.3\%$, $W_k = 19.4\%$, $q = 0.75$ kg/cu m, initiator 50 cu m CH_4; c — No. 3620: the d85 coal dust from the seam A713, $n = 48.4\%$, $n_p = 38.2\%$, $W_k = 21.1\%$, $q = 0.75$ kg/cu m, initiator 30mPII, the easiest dispersion conditions.

in the mining of coal all over the world water was regarded as the best and most reliable means of preventing the explosibility of coal dust.

The problem of coal dust explosions is rather complex and the use of water as a safeguard is justified provided that one has the elementary knowledge of the means of preventing coal dust explosions, and that the way in which water is used corresponds to the actual state of knowledge based on the results of experiments.

Investigations on the influence exerted by water upon the explosibility of coal dust were carried out in the *EM Barbara* very systematically taking into consideration all the most important parameters within the available conditions of experimenting. The basic investigations were carried out with the use of uniform mixtures of coal dust and water. These mixtures were prepared with the utmost care. The technical details concerning all of the investigations made are given in the publications [33].

The influence was investigated:

— of the content of water upon the explosibility of the so-called pure coal dust which means that the percentage content of water W sufficient to protect coal dust against propagating an explosion is determined,

— of the five kinds of initiators upon the value of W,

— of the conditions of dispersion upon the value of W,

— of the degree of the fineness of coal dust upon the value of W; the dust used was $d25$, $d85$ and $d100$,

— of the content of incombustible solid matter in the dust upon the value of W.

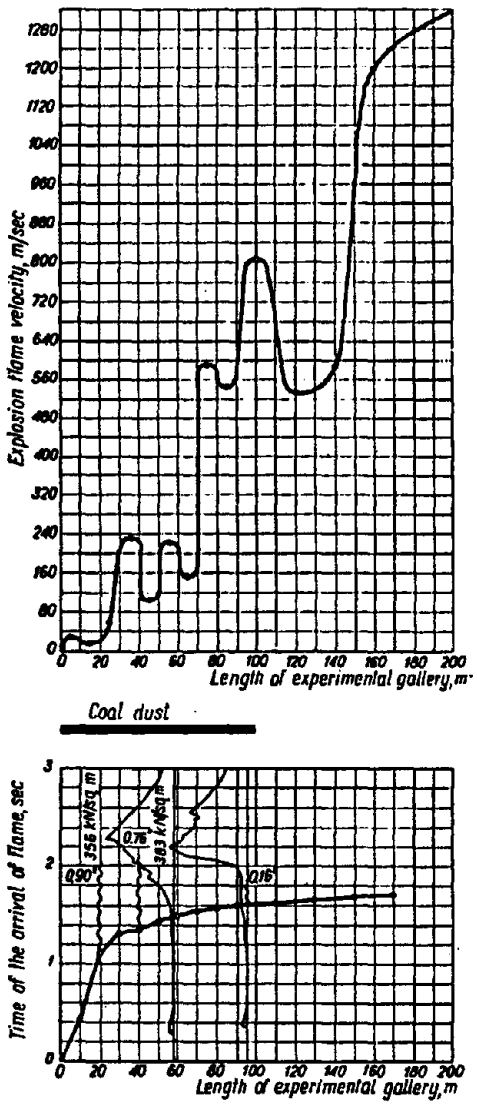


Fig. 3.14. A diagram of explosion No. 1931: the d85 *Barbara* coal dust, n = = 50%, n_p = 45%, W_K = 10%, q = 0.6 kg/cu m, direct initiator, the easiest dispersion conditions.

Detailed results of these investigations are contained in the publication [33]. Some results are given in Table 3.3.

Table 3.3 contains the following basic data concerning conditions, under which particular series of experiments were carried out, and the corresponding results:

W — free water for a given content of incombustible solid matter n_p;

C — content of d.a.f. coal in the mixture incapable of the propagation of an explosion;

S — explosibility of dry coal dust; this value had been found in previous researches for the given dust under identical conditions with those in which the relevant series of investigations were carried out on wet coal dust;

E_w — the relative effectiveness of water in comparison with the effectiveness of incombustible solid matter; E_w was calculated on the basis of the known values of S, n_p and W from the formula

$$E_w = \frac{S - n_p}{W} \tag{3.11}$$

Thus, E_w shows how many times water is more effective than incombustible solid matter in 100 weight units of the mixture; for some of the series of investigations the value of S had not been found and in such cases it was not possible to calculate the value of E_w;

X_w — the weight effectiveness of water expressed by the number of weight units of pure coal dust protected against explosion by a weight unit, for example, 1 kg of water;

X_s — the analogous to X_w weight effectiveness of incombustible solid matter,

$E_x = \frac{X_w}{X_s}$ — comparison between the effectiveness of identical quantities of water and incombustible solid matter; E_x, therefore, shows how many times a weight unit of water (e.g., 1 kg) is more effective than that of incombustible solid matter;

C_b — the weight amount of d.a.f. coal that can be protected against explosion by the weight quantities of n_p and W determined according to their respective effectiveness X_s and X_w.

Since for every given coal dust the value of W depends upon n it is necessary, when the dependence of the explosibility of coal dust upon the above parameters is considered, to keep in mind the elementary way of determining n. The value of n is calculated ordinarily for air-dry coal dust. The symbol n is used then to denote this value. This method of calculation is used as a rule when one verifies the content of incombustible

Table 3.3

Results of Investigations on the Explosibility of Wet Coal Dust and of Wet and Humid Mixtures of Coal Dust with Stone Dust

Initiator	Coal dust mixtures with water and stone dust								S, %	E_w	X_w	X_s	E_x	C_b
	dispersion conditions (floor, roof bars)	seam	d,%	pure dust with limestone or clay-slate dust	n, %	mixture unable to propagate explosions								
						n_p, %	C, %	W, %						
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direct	floor	*Barbara*	85	pure	18.5	16.1	71.4	$W_4=12.5$	47.5	2.512	4.288	1.105	3.880	—
Direct	roof bars	*Barbara*	25	pure	14.0	12.4	76.6	$W_6=11.0$	37.5	2.281	5.086	1.666	3.052	—
Direct	roof bars	*Barbara*	85	clay slate	50.0	42.5	42.5	$W_3=15.0$	72.5	2.000	—	—	—	—
4mPII	floor	*Barbara*	25	pure	13.5	12.8	82.2	$W_1=5.0$	—	—	—	—	—	—
4mPII	floor	*Barbara*	85	pure	17.5	14.1	66.9	$W_3=19.0$	60.0	2.415	3.020	0.666	4.543	—
4mPII	roof bars	*Barbara*	25	pure	16.0	13.9	73.1	$W_4=13.0$	45.0	2.392	4.316	1.222	3.531	—
15mPII	floor	*Barbara*	25	pure	16.0	12.2	64.3	$W_2=23.5$	62.5	2.140	2.425	0.600	4.041	—
15mPII	floor	*Barbara*	85	pure	17.0	11.5	56.5	$W_3=32.0$	77.5	2.062	1.662	0.290	5.731	—
15mPII	roof bars	*Barbara*	25	pure	16.0	11.8	62.2	$W_3=26.0$	70.5	2.238	2.198	0.428	5.135	—
15mPII	roof bars	*Barbara*	85	pure	16.5	10.7	54.3	$W_2=35.0$	80.0	1.980	1.475	0.250	5.900	—
50 cu m CH_4	floor	*Barbara*	25	pure	15.5	11.9	65.1	$W_5=23.0$	60.0	2.091	2.486	0.666	3.732	—
50 cu m CH_4	floor	*Barbara*	25	clay slate	30.0	25.8	60.2	$W_4=14.0$	60.0	2.442	—	—	—	51.9
50 cu m CH_4	floor	*Barbara*	25	clay slate	50.0	46.0	46.0	$W_6=8.0$	60.0	1.750	—	—	—	50.5
50 cu m CH_4	floor	*Barbara*	85	pure	13.5	8.8	56.2	$W_3=35.0$	75.0	1.891	1.523	0.333	4.573	—
50 cu m CH_4	floor	*Barbara*	85	clay slate	50.0	41.2	41.3	$W_3=17.5$	75.0	1.931	—	—	—	40.4
50 cu m CH_4	floor	*Barbara*	100	clay slate	60.0	49.2	32.8	$W_3=18.0$	—	—	—	—	—	—
50 cu m CH_4	floor	M 708	25	pure	11.0	8.5	68.5	$W_2=23.0$	60.0	2.239	2.732	0.666	4.102	—
50 cu m CH_4	roof bars	*Barbara*	25	pure	16.0	11.0	58.0	$W_2=31.0$	72.5	1.983	1.736	0.379	4.580	—
50 cu m CH_4	roof bars	*Barbara*	25	clay slate	50.0	42.5	42.5	$W_3=15.0$	72.5	2.000	—	—	—	42.1
50 cu m CH_4	roof bars	*Barbara*	85	pure	14.0	8.0	49.5	$W_2=42.5$	82.5	1.752	1.124	0.212	5.301	—
50 cu m CH_4	roof bars	*Barbara*	85	limestone	50.0	36.5	36.5	$W_5=27.0$	82.5	1.703	—	—	—	38.1

Table 3.3 (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
50 cu m CH_4	roof bars	*Barbara*	85	clay slate	50.0	37.5	37.5	$W_3=25.0$	82.5	1.800	—	—	—	36.0
50 cu m CH_4	roof bars	*Barbara*	85	limestone	60.0	48.0	32.0	$W_5=20.0$	82.5	1.725	—	—	—	32.6
50 cu m CH_4	roof bars	*Barbara*	85	clay slate	60.0	47.1	31.4	$W_6=21.5$	82.5	1.646	—	—	—	34.1
50 cu m CH_4	roof bars	*Barbara*	85	limestone	70.0	59.5	25.5	$W_1=15.0$	82.5	1.534	—	—	—	29.5
50 cu m CH_4	roof bars	*Barbara*	85	clay slate	70.0	61.2	26.3	$W_5=12.5$	82.5	1.704	—	—	—	27.0
50 cu m CH_4	roof bars	*Barbara*	100	clay slate	60.0	46.5	31.0	$W_3=22.5$	87.5	1.822	—	—	—	—
50 cu m CH_4	roof bars	*Barbara*	100	clay slate	70.0	59.5	25.5	$W_3=15.0$	87.5	1.866	—	—	—	—
30mPII	floor	*Barbara*	25	pure	15.0	10.5	59.5	$W_1=30.0$	70.0	1.983	1.833	0.428	4.282	—
30mPII	floor	*Barbara*	25	clay slate	50.0	43.5	43.5	$W_3=13.0$	70.0	2.038	—	—	—	42.5
30mPII	floor	*Barbara*	85	pure	9.5	5.1	49.9	$W_7=45.0$	82.5	1.718	1.084	0.212	5.113	—
30mPII	floor	*Barbara*	85	limestone	50.0	38.5	38.5	$W_1=23.0$	82.5	1.913	—	—	—	33.1
30mPII	floor	*Barbara*	85	clay slate	50.0	39.0	39.0	$W_3=22.0$	82.5	1.977	—	—	—	31.1
30mPII	floor	M 708	85	pure	9.5	6.0	57.5	$W_1=36.5$	77.5	1.957	1.526	0.290	5.262	—
30mPII	floor	*Barbara*	100	clay slate	23.0	32.5	32.5	$W_1=35.0$	—	—	—	—	—	—
30mPII	roof bars	*Barbara*	25	pure	15.0	9.7	55.3	$W_1=35.0$	75.5	1.865	1.485	0.333	4.459	—
30mPII	roof bars	*Barbara*	25	clay slate	50.0	41.2	41.3	$W_8=17.5$	75.5	1.928	—	—	—	39.8
30mPII	roof bars	*Barbara*	25	clay slate	65.0	58.1	31.4	$W_4=10.5$	75.5	1.609	—	—	—	35.0
30mPII	roof bars	A 713	25	pure	17.0	11.9	58.1	$W_1=30.0$	70.0	1.936	1.767	0.428	4.128	—
30mPII	roof bars	*Barbara*	85	pure	15.0	7.9	44.6	$W_1=47.5$	87.5	1.676	0.916	0.142	6.450	—
30mPII	roof bars	*Barbara*	85	limestone	50.0	35.5	35.5	$W_4=29.0$	87.5	1.793	—	—	—	31.6
30mPII	roof bars	*Barbara*	85	clay slate	50.0	36.5	36.5	$W_5=27.0$	87.5	1.888	—	—	—	29.5
30mPII	roof bars	A 713	85	pure	16.0	9.3	48.7	$W_1=42.0$	80.0	1.683	1.104	0.250	4.416	—
30mPII	roof bars	A 713	85	limestone	48.0	34.5	37.5	$W_2=28.0$	80.0	1.625	—	—	—	39.5
30mPII	roof bars	*Barbara*	100	pure	25.0	14.5	43.5	$W_1=42.0$	90.0	1.797	0.997	0.111	8.981	—
30mPII	roof bars	*Barbara*	100	clay slate	70.0	54.0	28.0	$W_1=18.0$	90.0	1.811	—	—	—	23.9

solid matter in the mine dust according to regulations. However, when investigations are carried out, or their results are being applied in practice, the content of incombustible solid matter in the dust is calculated in relation to the dust with natural content of free water — that is, the content of incombustible solid matter n_p is determined in relation to the natural dust, which is called in short: wet dust. Of course when we deal with dry dust exclusively, the determining of the value n_p is out of the question. Attention should be drawn to these two basic methods because the pertinent dependence may be determined in different ways depending on the fact whether the value n, or the value n_p is to be used.

In Fig. 3.15 is presented graphically the dependence of W upon the content of incombustible soild matter n_p in the wet dust, upon the initiators of explosions, the fineness and conditions of dispersion of coal dust

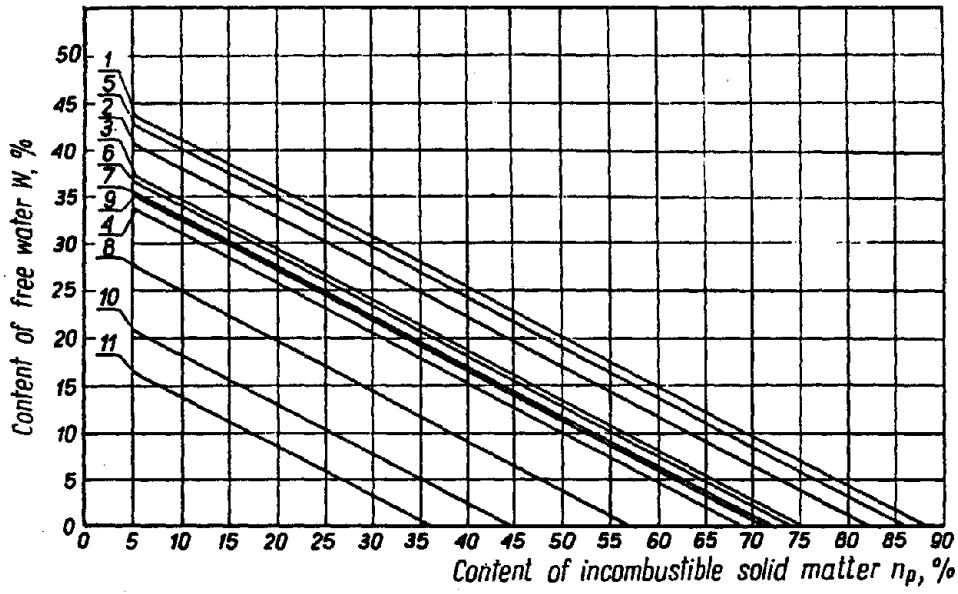


Fig. 3.15. Diagrams of the dependence of the content of free water W upon the content of incombustible solid matter n_p in wet dust in mixtures incapable of propagating explosions: *1* — initiator 30mPII, *d*85 dust, roof bars; *2* — initiator 30mPII, *d*85 dust, the floor; *3* — initiator 30mPII, *d*25 dust, roof bars; *4* — initiator 30mPII, *d*25 dust, the floor; *5* — initiator 50 cu m CH_4 *d*85 dust, roof bars; *6* — initiator 50 cu m CH_4, *d*85 dust, the floor; *7* — initiator 50 cu m CH_4, *d*25 dust, roof bars; *8* — initiator 50 cu m CH_4, *d*25 dust, the floor; *9* — direct initiator, *d*85 dust, roof bars; *10* — direct initiator, *d*85 dust, the floor; *11* — direct initiator, *d*25 dust, roof bars.

from the *Barbara* seam. The graphs were drawn on the basis of data contained in Table 3.3. As can be concluded from Fig. 3.15 the interdependence

between W and n_p is a rectilinear one (in an analogous case the dependence of W upon n cannot be expressed by a first degree equation). 8he content of W refers to the wet dust and all the points of the line (Fig. 3.15) correspond to parameters which make the given coal dust incapable of propagating an explosion.

The diagram in question refers only to coal dust from the *Barbara* seam and takes account of only three kinds of initiators. The two initiators omitted, namely, 4mPII and 15mPII, as well as the results obtained with reference to coal dust from the seams A 713 and M 708, produced lines parallel to the ones included in Fig. 3.15.

The influence exerted by all of the examined parameters upon the value of W is very clearly presented in both Fig. 3.15 and Table 3.3. For instance, in the case of the *d*25 *Barbara* dust and the initiators: direct, 4mPII, 15mPII, 50 cu m CH_4 and 30mpII under the most favorable dispersion conditions, the values of W were found to be, respectively: 11, 13, 26, 31 and 35 percent. For the identically arranged sequence of initiators, under the most difficult conditions of dispersion, in the case of the *d*85 *Barbara* dust the corresponding values of W were: 12.5, 19, 32, 35 and 45 percent.

On the whole, on the basis of the results given in Table 3.3. it can be seen how great is the influence of the explosion initiator upon the value of W; this influence grows with the increase in the strength of the initiator. The influence of the fineness of the dust on the value of W is also more pronounced when the differences between the strengths of particular initiators become greater. It is a noteworthy fact that, when the very strong initiator 30mPII is used the influence exerted by the conditions of dispersion on the value of W becomes less marked.

In order to facilitate a comparison between the influences exerted by the particular parameters of the explosibility of coal dust upon the value of S and the value of W a graphic representation in Fig. 3.16 gives the following:

— the values of S from the *Barbara* dry dust depending on the kind of the explosion initiator (Fig. 3.16*a*),

— the values of W in mixtures with pure *Barbara* coal dusts depending on the kind of the explosion initiator (Fig. 3.16*b*),

Figure 3.16 makes it possible, at the same time, to compare visually the effectiveness of incombustible solid matter and of water as a protection against the propagation of explosions.

The comparison between, and the summing up of, the characteristic magnitudes found through the investigation of the influences exerted by separate parameters upon the explosibility of the *Barbara* coal dust in mixtures with water are given in Table 3.4.

Table 3.4

Characteristic Magnitudes Found during the Investigations on the Influence of Particular Parameters upon the Explosibility of the Mixture of the *Barbara* Coal Dust with Water

Initiator	Dispersion conditions (location of dust)	Parameters	Pure coal dust from the *Barbara* seam			
			*d*25		*d*85	
Direct	floor	W	—		12.5	
		E_w E_x	—	—	E_w 2.512	E_x 3.880
		X_w X_s	—	—	X_w 4.288	X_s 1.105
	roof bars	W	11.0		—	
		E_w E_x	E_w 2.281	E_x 3.052	—	—
		X_w X_s	X_w 5.086	X_s 1.666	—	—
4mPII	floor	W			19.0	
		E_w E_x	—	—	E_w 2.415	E_x 4.543
		X_w X_s	—	—	X_w 3.026	X_s 0.666
	roof bars	W	13.0		—	
		E_w E_x	E_w 2.392	E_x 3.531	—	—
		X_w X_s	X_w 4.316	X_s 1.222	—	—
15mPII	floor	W	23.5		32.0	
		E_w E_x	E_w 2.140	E_x 4.041	E_w 2.062	E_x 5.731
		X_w X_s	X_w 2.425	X_s 0.600	X_w 1.662	X_s 0.290
	roof bars	W	26.0		35.0	
		E_w E_x	E_w 2.238	E_x 5.135	E_w 1.980	E_x 5.900
		X_w X_s	X_w 2.198	X_s 0.428	X_w 1.475	X_s 0.250
50 cu m CH_4	floor	W	23.0		35.0	
		E_w E_x	E_w 2.091	E_x 3.732	E_w 1.891	E_x 4.573
		X_w X_s	X_w 2.486	X_s 0.666	X_w 1.523	X_s 0.333
	roof bars	W	31.0		42.5	
		E_w E_x	E_w 1.983	E_x 4.580	E_w 1.752	E_x 5.301
		X_w X_s	X_w 1.736	X_s 0.379	X_w 1.124	X_s 0.212
30mPII	floor	W	30.0		45.0	
		E_w E_x	E_w 1.983	E_x 4.282	E_w 1.718	E_x 5.113
		X_w X_s	X_w 1.833	X_s 0.428	X_w 1.084	X_s 0.212
	roof bars	W	35.0		47.5	
		E_w E_x	E_w 1.865	E_x 4.459	E_w 1.676	E_x 6.450
		X_w X_s	X_w 1.485	X_s 0.333	X_w 0.916	X_s 0.142

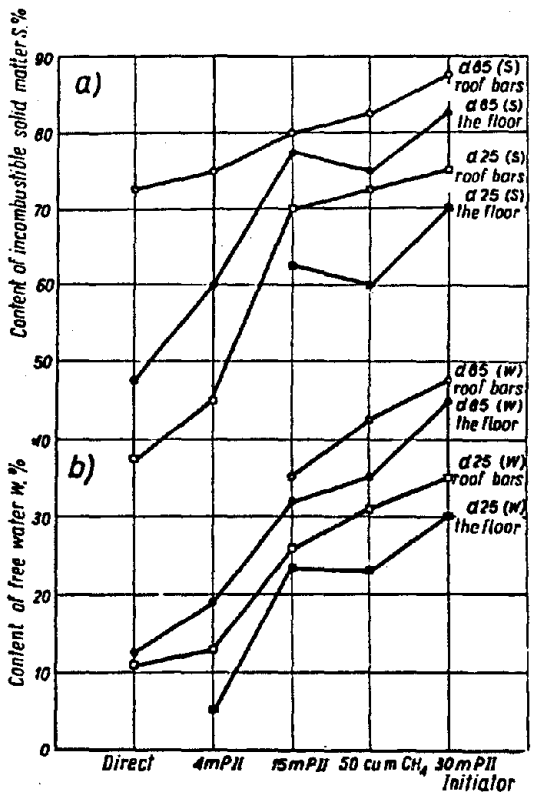


Fig. 3.16. A graphic presentation: *a* — of the dependence of the value *S* for the *Barbara* dry dust upon the explosion initiator; *b* — of the dependence of the value *W* in mixtures with pure *Barbara* coal dusts likewise upon the explosion initiator.

3.4.4. General information of a practical nature resulting from the investigations on the explosibility of wet mine dusts

The results of investigations on the influence exerted by water upon the explosibility of coal dust of a medium degree of fineness are of a very big direct practical importance in Polish conditions since coal dusts of a similar fineness are found most frequently in our mines.

As far as weak explosion initiators are concerned, such as the direct initiator and the 4mPII initiator, the medium pure dust can be protected against the propagation of an explosion by relatively low contents of water. In the case of the dust containing rather large quantities of incombustible solid matter — and this occurs most frequently in practice — the values of *W* are still lower. Also against a small local explosion of firedamp the medium coal dust is adequately protected by low water contents.

Even in the case of a strong initiator, such as the explosion of 50

cu m CH_4, the value of W for the *d*25 dust deposited on the floor of a gallery is relatively low provided that this dust contains incombustible solid matter in a quantity usually found in the mine. In Fig. 3.17*a* a graph is shown, by way of an example, representing the course of the explosion No. 2030. As can be seen in Fig. 3.17*a*, after the fading of the direct impact of the initiator, the explosion of the dust developed with a marked acceleration of the velocity of the flame with a corresponding increase in the pressure of the explosion up to 180 kN/sq m in proportion to the increase in the distance from the face of the gallery. This example is interesting because the same kind of dust, under exactly the same conditions, when the content of water in the dust had been increased by 4 percent — that is, to 14 percent, regularly failed to propagate explosions.

A fine dust requires a much higher content of water to be protected against the propagation of an explosion. Consequently, it presents a more serious danger than a medium dust. Even in the case of weak explosion initiators the values of W for fine dusts are relatively high. As an example in Fig. 3.17*b* a graph is shown representing the course of the propagated explosion No. 2011. The course of this explosion was very characteristic of a case in which a weak initiator had been used and dispersion conditions were of the most difficult kind. In Fig. 3.17*c* the graph represents the course of the propagated explosion No. 2010. The investigation was carried out under conditions quite analogous to those which existed in the case of the explosion No. 2011. The only difference consisted in the water content which was lower by 3 percent — that is, $W_k = 12.4$ percent. This small difference in the content of water in the dust had a great influence on the course of the explosion. The acceleration of the flame velocity was considerably higher. This velocity exceeded 1000 m/sec and the pressure was higher than 303 kN/sq m.

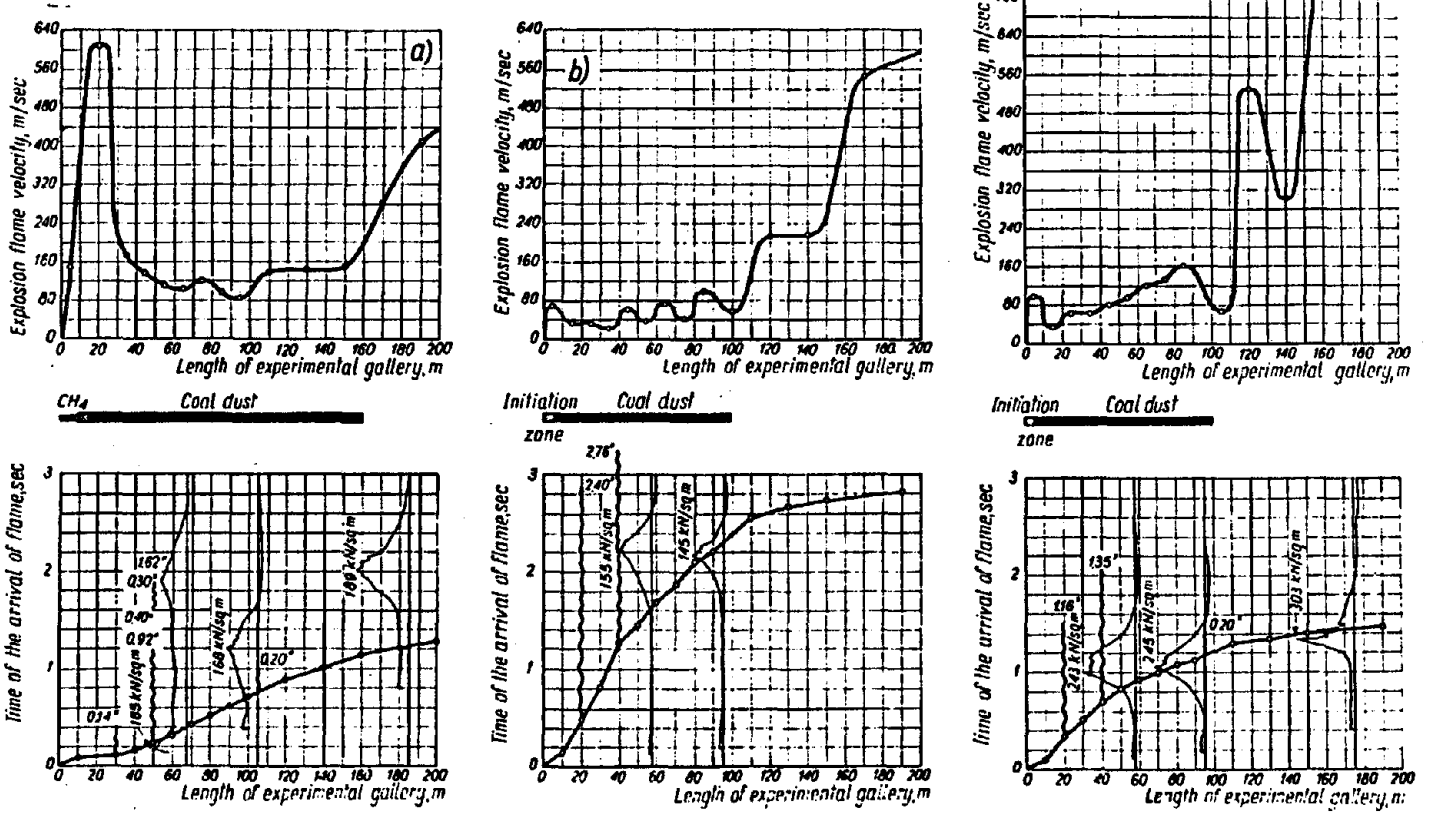
It should be mentioned that the examples quoted refer to the most difficult conditions of dispersion.

In the cases represented in previous figures, where dispersion conditions were the most favorable, the development of explosions was much more violent (e.g., Fig. 3.14). Under conditions of the most favorable dispersion the pure *d*85 *Barbara* coal dust, even when its water content $W_k = 45.3$ percent, did propagate an explosion.

When strong or very strong initiators were used such as the initiators: 15mPII and 50 cu m CH_4, as well as 30mPII, the contents of water W protecting pure dusts exceeded considerably the contents of water W_L depriving the dust of its dispersibility according to the graphs given in Fig. 3.11.

When the very strong initiator 30mPII was used, in the case of pure *d*25 dust deposited on the floor of a gallery, $W = 30$ percent. For the same

Fig. 3.17. Diagrams of explosions: a — No. 2030: the d25 *Barbara* coal dust, $n = 30\%$, $n_p = 27\%$, $W_k = 10\%$, q = 2 kg/cu m, initiator 50 cu m CH_4, the most difficult dispersion conditions; b — No. 2011: the d85 *Barbara* coal dust, $n = 19.4\%$, $n_p = 16.4\%$, $W_k = 15.4\%$, $q = 2$ kg/cu m, initiator 4mPII, the most difficult dispersion conditons; c — No. 2010: same conditions as in explosion No. 2011 except that $W_k = 12.4\%$.



dust deposited on roof bars $W = 35$ percent. Note that the d25 dust containing 27 percent of water was so wet that, when it was squeezed in the palm of the hand, water leaked from it. In Fig. 3.18*a* the propagated explosion No. 3605 of this series of experiments is presented graphically.

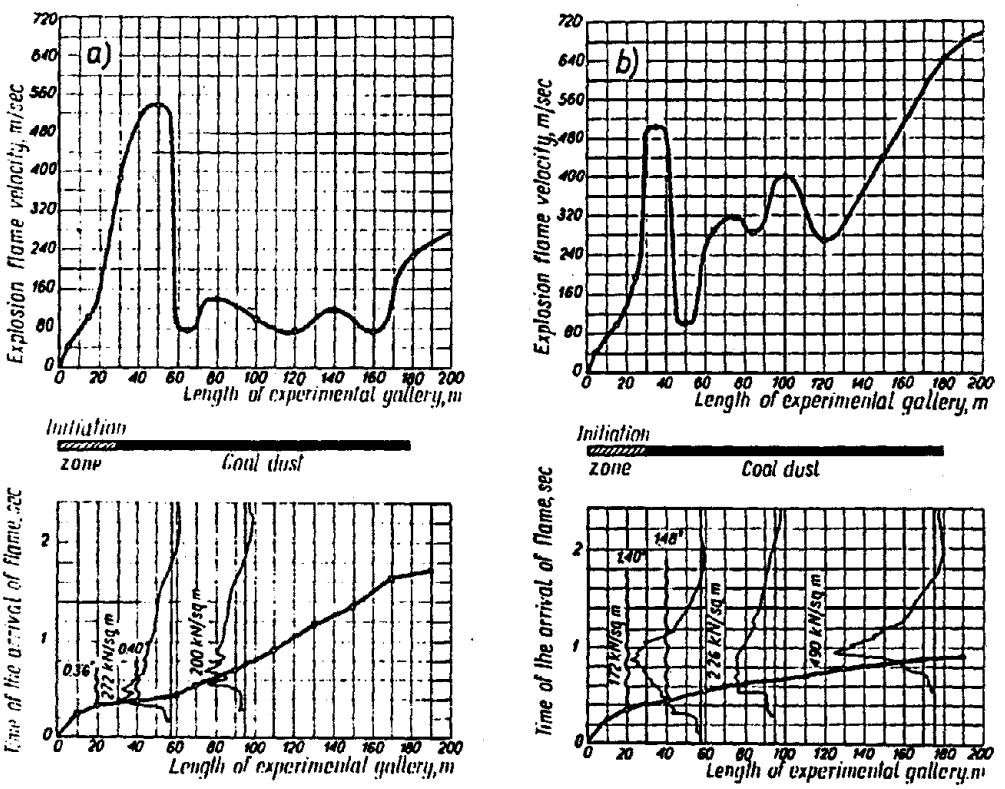


Fig. 3.18. Diagrams of explosions: *a* — No. 3605: the d25 *Barbara* coal dust, $n = 14\%$, $n_{\text{p}} = 10.1\%$, $W_{\text{k}} = 27.8\%$, $q = 2$ kg/cu m, initiator 30mPII, the most difficult dispersion conditions; *b* — No. 3553: the d85 *Barbara* coal dust, $n = 14.9\%$, $n_{\text{p}} = 9.2\%$, $W_{\text{k}} = 38.1\%$, $q = 0.5$ kg/cu m, initiator 30mPII, the easiest dispersion conditions.

When the initiator used was 30mPII it has been necessary, in order to protect pure d85 dust, to bring water contents up to 50 percent. The values of W, found in experiments carried out under the two dispersion conditions applied in the investigations, are similar to each other in the case of both d85 and d25 dusts.

It should be stated generally that when it comes close to the limit water contents, near to the values likely to safeguard coal dust against the propagation of explosions, small differences in the percentage of water bring in effect big differences in the course of explosions. In Fig. 3.18*b* the explosion No. 3553 is graphically represented which was initiated

under conditions quite analogous to those in which the explosion shown in Fig. 3.13*a* had been initiated, the only difference being in the contents of water which amounted to $W_k = 38.1$ percent. The fact that water contents were reduced by 7.2 percent resulted in the velocity of the explosion showing a marked acceleration reaching up to 700 m/sec.

The maximum pressure registered in the course of explosions of wet fine *Barbara* pure dust was 680 kN/sq m. Actually this was not the maximum pressure which occurred in the course of these investigations. When explosions were of great violence the instrument registering the pressure at the furthest measuring point suffered a breakdown more often than not and, in consequence, the highest pressure was not registered.

It should be underlined that these experiments were not intended to investigate the most violent wet explosions. Actually one tried to avoid such explosions on account of damages to experimental galleries caused by them. The damages actually done to the steel support proved also that pressures occurring in the course of explosions had to be much higher than the registered ones.

3.4.5. Comparison between the efficiency of water and of stone dust

In Table 3.4 are listed values of X_w, E_x and E_w which refer to pure coal dusts from the *Barbara* seam.

The weight effectiveness of water X_w depends, obviously, on the explosion initiator, on the conditions of dispersion and on the degree of fineness of the dust since the degree of the explosibility of coal dust depends upon these parameters.

With the increase in the strength of the explosion initiator the weight effectiveness of water X_w declines as declines also the weight effectiveness of incombustible solid matter X_s.

This is illustrated by the following examples:

— for *d*25 dust deposited on roof bars:
  $X_w = 5.09$ when the direct initiator is used,
  $X_w = 1.48$ when the 30mPII initiator is used;

— for *d*85 dust deposited on the floor:
  $X_w = 4.29$ when the direct initiator is used,
  $X_w = 0.92$ when the 30mPII initiator is used.

The effectiveness of water in comparison with the effectiveness of stone dust, expressed by the magnitude of E_x, does not change materially depending on the explosion initiator used. The value of E_x is slightly lower when the initiators are weak. This is explained by the fact that the influence of strong initiators upon the explosibility of dry coal dust is more effective than it is in respect of wet dust.

The weight effectiveness of water X_x is a little higher in the case of coal dust deposited on a gallery floor than it is in the case of coal dust on roof bars. On the other hand the effectiveness of water in comparison with that of stone dust E_x is higher in the case of coal dust placed on roof bars than in the case of coal dust deposited on the gallery floor. This is explained by the fact that, in the case of strong explosion initiators, conditions of the dispersion of dust exert a stronger influence on the explosibility of dry coal dust than on that of wet dust.

The weight effectiveness of water X_w is higher with regard to *d*25 coal dust than with regard to *d*85 coal dust. On the other hand, the effectiveness of water in comparison with the effectiveness of stone dust E_x is higher with regard to *d*85 coal dust than with regard to *d*25 coal dust. This is so because the influence of the fineness of coal dust on its explosibility is stronger in the case of dry dust than in the case of wet dust. In Table 3.5 are listed the mean comparative values of the effectiveness of the same weight quantities of water and of stone dust E_x with regard to pure coal dusts from the *Barbara* seam. Thus it can be accepted that water is approximately five times as effective as stone dust when the effectiveness is compared of the same weight quantities of water and of stone dust. It ought to be underlined that the comparison pertains to mixtures of coal dust with water and to mixtures of coal dust with stone dust.

Table 3.5

The Mean Comparative Values of the Effectiveness of the Same Weight Quantities of Water and of Stone Dust E_x for Pure Coal Dusts from the *Barbara* Seam

Initiators	Dispersion conditions	Values of E_x for dusts	
		*d*25	*d*85
Weak	floor	—	4.2
	roof bars	3.3	—
Strong	floor	4.0	5.2
	roof bars	4.7	5.9

The relative effectiveness of water in comparison with the effectiveness of incombustible solid matter E_w depends, naturally, also upon the explosion initiator, the conditions of dispersion and the degree of the fineness of the dust. As can be seen from data given in Table 3.4 the values of E_w decline on the whole with the increase in the strength of the explosion initiator used; for example, in the case of the d85 dust on the

gallery floor, when the direct initiator is used, $E_w = 2.51$ but when the 30mPII initiator is applied — $E_w = 1.72$.

Under the conditions of the most difficult dispersion the values of E_w were, generally, slightly higher than under the most favorable dispersion conditions. These values were somewhat higher in the case of the $d25$ dust than in the case of the $d85$ dust.

The opposite directions of the changes in the values of E_x and E_w discussed here are the natural result of the different construction of these two magnitudes.

3.4.6. The explosibility of wet mixtures of coal dust with stone dust

When high amounts of water are contained in mixtures of coal and stone dusts both these dusts lose their dispersibility. Low contents of water diminish the dispersibility of these dusts in various degrees. Water diminishing the dispersibility of both these dusts decreases the explosibility of coal dust but, at the same time, it diminishes also the effectiveness of stone dust. Apart from this, as the quantity of stone dust contained in the mixture increases, the share of coal dust in the absorption of water, added to the mixture of coal dust with stone dust, becomes lower.

The elucidation of the question: whether the effectiveness of water, determined with regard to pure coal dusts, is the same as its effectiveness with regard to mixtures of coal dust with stone dust is of a fundamental importance. On the basis of the results of 19 series of investigations [33] it has been established that, within the limits of the accuracy of the relevant experiments, water is as effective with regard to mixtures of coal dust and stone dust as it is when mixed with pure coal dust.

With the increase in the content of incombustible solid matter n in the dust the value of W naturally decreases. The results of investigations concerning this interdependence are shown in Fig. 3.15. The diagram presented in this figure makes it possible to find, for every walue n_p (for wet dust), the corresponding value of W for a given dust and a given explosion initiator. The diagram in question is of a direct practical importance since it helps to establish the degree of the danger presented by the particular dust depending upon its contents of incombustible solid matter and of water. The interdependences in question are expressed mathematically further in this book. Of course a mathematical presentation is more valuable because, in respect of coals from different seams, the graph would naturally assume somewhat different shapes. It is worth noticing, however, that the graphs which pertain to the dust from the *Barbara* seam may be used with a sufficient margin of safety in connection with dusts from other seams, taking into account the fact that the dusts from the *Barbara* seam belong to the most explosive kinds. The diagram in Fig. 3.15 may

be used in connection with coals containing > 25 percent of volatile matter.

Investigations concerning the explosibility of wet mixtures of coal dust with limestone dust and with clay-slate dust have disclosed no material differences between the effectiveness of these stone dusts under conditions of wet mixtures.

Therefore, it is possible to assume that stone dust from the crushed strata, as well as limestone dust used for dusting mine workings, show practically the same effectiveness in wet mixtures with coal dust.

According to American investigators [129] the effectiveness of water can be increased with the aid of a saturated solution of ammonium phosphate or of a mixture of this chemical with stone dust.

3.4.7. Investigations on the efficiency of wetting agents in mixtures of water with coal dust

The established facts of very violent explosions of coal dust, saturated with water well beyond the point at which the dust loses completely its dispersibility, necessarily suggest the fundamental question as to what is the course of the explosion under such conditions. In this connection the question may be raised whether the propagation of an explosion of very wet coal dust, prepared by mixing the dry dust with water, is not caused by the insufficient covering of the surface of the grains of the dust with water. To elucidate this question experiments were made in which very good wetting agents were added to water. These agents aid very effectively in the uniform adsorption of water by coal dust, the water covering very well the surface of all fractions of the comminuted coal. Experiments carried out with four kinds of wetting agents showed that the values of W, within the limits of the accuracy of experiments, were the same when pure water was used as when the water used in the experiments had wetting agents added to it. It should be mentioned that experiments were made with coal dust containing large quantities of incombustible solid matter as well as with pure coal dust.

These experiments supplied the proof that the cause of the propagation of explosions of very wet coal dust lies not in the unsatisfactory covering with water of the surface of separate dust grains.

The results of these experiments should not be interpreted, however, as an indication that wetting agents — that is, surface-active substances, are not helpful in the processes of spraying coal dust with water. Under conditions prevailing in mines wetting agents added to water undoubtedly help to deprive coal dust of its dispersibility. Dry coal dust does not easily

absorb water. When wetting agents are added this process is made much easier. Consequently, the use of wetting agents with water in order to deprive dry coal dust of its dispersibility is certainly to be recommended provided that the wetting agent used is not harmful to the health — that is, that it does not affect the skin or the respiratory system. The experiments discussed above were carried out with uniform mixtures of pure water with coal dust and of water with wetting agents added to it with coal dust. The very process of wetting coal dust — particularly in conditions prevailing in mines — is greatly facilitated when wetting agents are added to water because, when spraying with water is applied in mines, the water is not mixed with the dust in the manner in which this is done in the course of experimenting.

Coal dust absorbs water easily when it already contains a certain percentage of natural humidity. For this reason the spraying with water in the mining practice can be recommended only when coal dust is already sufficiently humid — that is, when it is uniformly saturated with natural humidity. This rather important question will be discussed again in a later part of this book when the application of spraying with water will come up for consideration as a means of making coal dust safe.

3.4.8. The course of phenomena occurring in explosions of wet coal dust

The question arises: what may be the course of phenomena occurring with explosions of coal dust so thoroughly saturated with water that its mixtures are of the consistency of mud — that is, they contain a considerable excess of water over the possibility of its absorption. It is known that such explosions can take place only when very strong initiators are used. There is no doubt that such initiators must produce a very strong blast which raises a part of the mass of dust, and causes its dispersion in a certain measure. This dispersion, however, cannot be such as would have occurred in the case of dry coal dust. The fact that a mass of dust is raised to the air has been confirmed by observations made after explosions: on the fronts of roof bars and on the props, layers of newly cast coal dust were usually found.

Strong initiators produce flames of a very long range. The range of the explosion flame of the 50 cu m CH_4 initiator, in a gallery a cross section of which measures 7.5 sq m, exceeds 30 m; in a gallery whose cross section measures 5 sq m it exceeds 50 m; and when the gallery's cross section is 3 sq m the range of the flame is 80 m. The range of the flame of an explosion initiated by the 30mPII initiator exceeds 90 m. In these cases the flame fills the entire cross section of the gallery throughout the major part of the zones mentioned. The dust raised by the blast of the

initiator becomes encompassed by the flame in the zone of the flame's range. Agglomerations of the raised dust dry up in consequence of this and the dust becomes capable of exploding. The dust which was not raised to the air is made dry only partly on the surface by the action of the flame of the initiator, and can also participate in the explosion.

In the case of what are called the most difficult dispersion conditions, when wet coal dust is deposited only on the gallery's floor, the dispersion of the surface layer of wet dust is more difficult than in the case when this dust is deposited on roof bars. However, in the most difficult conditions of dispersion a considerably larger surface of the wet coal dust is exposed to the drying action of the flame of the initiator than in the case of the easiest dispersion and, therefore, a part of the dust is raised to the air. This can be the explanation of the fact that the values of W, found for each of the two dispersion conditions in which experiments were made, differ but slightly when strong and very strong explosion initiators are used such as 15mPII, 50 cu m CH_4 and 30mPII. The primary cloud of dust, of course, augments the direct impact of the initiator — just as it does in the case of a dispersible dust — increasing the effects of the blast and the quantity of the heat energy. The increased heat energy causes evaporation of water from the dust raised to the air as well as from the wet surface of the mass of dust which had not been raised to the air.

As was mentioned already, when the initiators of explosions are strong, the value of W practically does not change with the change of the conditions of the dispersion of dust. This fact is worthy of a special study considering the marked difference between the course in which explosions of wet coal dust develop under the two different dispersion conditions.

The fact that in the case of dry coal dust the same value of S is found, regardless of the dispersion conditions when strong initiators are used, is quite comprehensible. A strong initiator, because of the high energy of its blast, can raise from a gallery's floor a sufficient quantity of dust and disperse this dust in a sufficiently uniform way throughout the entire cross section of the gallery.

On the other hand, in the case of a very wet coal dust the convergency of the values of W under both dispersion conditions can be given an explanation analogous to that given above in the case of dry dust, but the fact must still be considered that the raising of a very wet dust from the floor of a gallery and dispersing it throughout the entire cross section of the gallery is certainly much more difficult than it is in the case of dry dust. Though these phenomena present very interesting aspects no special research work was undertaken for the purpose of their elucidation.

In connection with the considerations presented above it is of considerable interest to establish the extent to which wet coal dust dries up in

the course of an explosion. Many experiments were carried out in order to find the answer to this question. The establishing of the content of free water in the dust, remaining after an explosion in the experimental gallery, presents very serious difficulty on account of the fact that, after an explosion, there are left in the gallery large quantities of carbon monoxide. The collection of samples of the dust by a rescue team is a dangerous undertaking so that only with great precautions and to a relatively limited extent it has been possible to collect the necessary samples. The results obtained from the examination of these samples cannot be regarded as very precise since, on account of the danger referred to above, it was not possible to collect the samples of dust in a manner answering the requirements of the statistical method. Nevertheless, these results are the only known ones obtained from investigations carried out on such a scale.

In the course of investigations on the explosibility of wet coal dusts, of course facts of propagation, as well as facts of nonpropagation, of explosions were established. This was necessary in order to find the limit value of W. Accordingly, the researches concerning the content of water in the dust left after explosions were carried out after both propagated and nonpropagated explosions.

After the propagated explosions the content of W_k in the dust diminished by from 10.7 to 54.4 percent of the original magnitude — that is, by 32.5 percent on the average.

After the nonpropagated explosions the value of W_k diminished by from 4.3 to 19.9 percent — that is, by 11 percent on the average.

It should be added that the above limit figures refer to samples collected from the entire gallery not to single samples of dust.

Though the results obtained serve only to orient ourselves in the problem they show, nevertheless, that the drying up of the dust after explosions was quite considerable.

Note that the samples collected represented the entire dust remaining in the gallery. The evaporation of water from the surface layers of the dust in the course of the explosion must have been much higher. The long time during which the explosion flame acted on the dust brought about a higher evaporation of water than that which occurs in the zone of the decisive influence upon the course of the explosion (Section 2.3.2.2).

In connection with propagated explosions, especially very violent ones, coal dust clouds were observed jetting with extreme force from the experimental gallery to the surface.

In Fig. 3.12*a* is shown the ejection produced in the course of the explosion No. 3574 of fine *Barbara* coal dust in which water content $W_k = 37.3$ percent. The picture of the dust clouds leaves no doubt that the

dust in question had been dry enough to be dispersed in the shape of typical clouds. The diagram of this explosion is shown in Fig. 3.19.

When investigating the explosibility of wet coal dusts attention is drawn to the fact that, with water contents only relatively slightly lower than the value of W, explosions can still be very violent. No similar phenomenon is observed when the limit contents of incombustible solid matter are being determined.

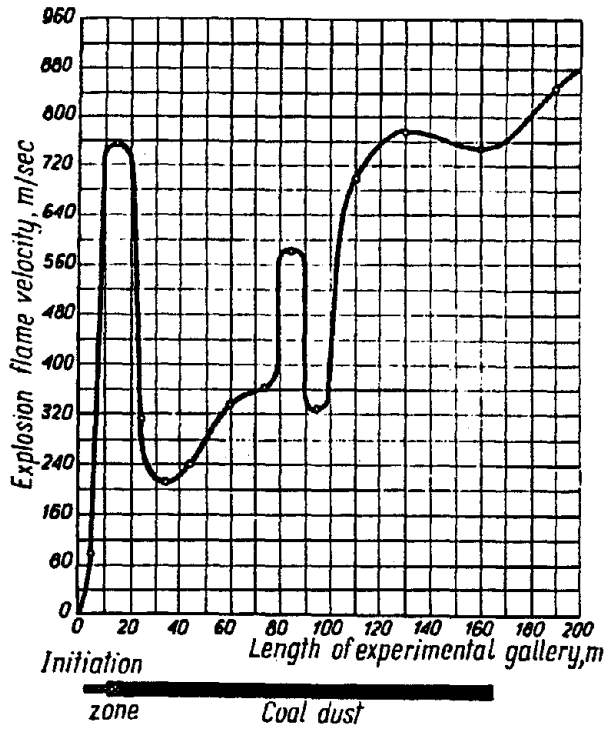


Fig. 3.19. A diagram of the flame velocity in explosion No. 3574: the d85 *Barbara* coal dust, n = 13.7%, n_p = 8.5%, W_k = 37.3%, q = 0.5 kg/cu m, initiator 50 cu m CH_4, the easiest dispersion conditions.

In order to avoid any misunderstanding it is necessary to explain that — when stone dust contents are much lower than the limit value of S — very violent explosions might occur. However, when the contents of incombustible matter are only slightly lower than S explosions which take place are much milder than those that occur under analogous conditions in the course of experimenting with wet coal dusts.

The great violence of explosions of wet coal dusts suggests a supposition that at the time when these explosions take place a decomposition of steam by the incandescent particles of coal occurs according to the equation

$$H_2O + C = CO + H_2 \tag{3.12}$$

or to the equation

$$2H_2O + C = CO_2 + 2H_2 \tag{3.13}$$

Considering the high temperatures created during explosions the reaction should rather evolve according to equation (3.12). Unfortunately the examination of the composition of gases directly behind the front of the flame presented too great experimental difficulties. Samples were collected immediately after the explosion. The analyses of the samples of gases from 18 propagated explosions of wet coal dust disclosed the following average contents:

H_2 — 2.42%
CO — 5.39%

Under the analogous conditions samples of gases were collected after explosions of dry coal dust. The analysis of such samples, collected from 90 propagated explosions, disclosed the following average contents:

H_2 — 1.26%
CO — 2.91%

As can be seen, in the case of the explosions of wet coal dust the contents of H_2 and of CO are approximately twice as high as in the case of the explosions of dry coal dust.

3.4.9. Comparison between the results of Polish and foreign investigations

In the *EM Bruceton*, USA, investigations on the explosibility of mixtures of coal dust from the seam *Pittsburgh* with water and with slate stone dust were carried out. Coal from the *Pittsburgh* seam contained 36.4 percent of volatile matter [139]. Though investigations were carried out by American research workers on a narrower scale than corresponding Polish investigations, yet a comparison between the results of these investigations is very valuable. The initiator of explosions used in USA is very similar to the Polish initiator 15mPII and, besides, the degree of the fineness of the coal dust used in experiments was frequently the same as that of the dust used in Poland. Figure 3.20 presents the results of American investigations, as well as the results of Polish investigations, expressed graphically. The curves shown in Fig. 3.20 represent the interdependence between water content W in the mixtures and the entire content of incombustible matter in the mixtures found to be limiting in respect of their explosibility. The entire content of incombustible matter represents the sum of free water and incombustible solid matter.

For comparative purposes in the same figure four curves are shown representing analogously the results of investigations carried out in the *EM Barbara* on fine and medium coal dust with the use of the initiator 50 cu m CH_4 under conditions of both the easiest and the most difficult dispersion. Note that the curves representing the results of Polish investigations refer to contents of water and of incombustible solid matter at which, as has already been established, a propagation of explosion does not occur. One can consider the *d85 Barbara* dust to be approximately equivalent to the American *75 percent 200* dust in respect of the fineness. The *d25 Barbara* dust may also be considered to be of approximately the same degree of fineness as the American *20 percent 200* dust.

As can be seen the difference between the results obtained in the

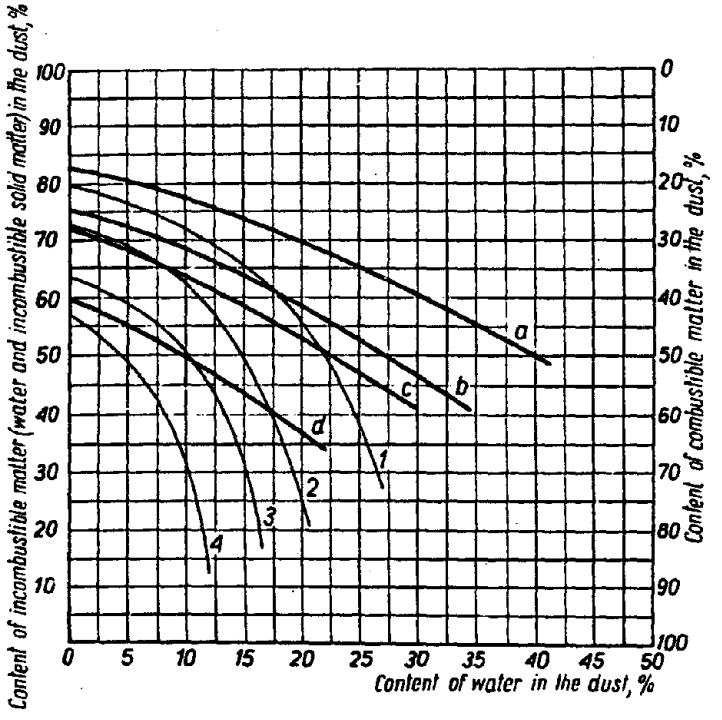


Fig. 3.20. A comparative diagram of the results of Polish and American investigations on the influence of free water upon the explosibility of coal dust depending on the content of incombustible matter in the dust; Polish results: *a* — the *d85 Barbara* coal dust, roof bars, 50 cu m CH_4; *b* — the *d85 Barbara* coal dust, the floor, 50 cu m CH_4; *c* — the *d25 Barbara* coal dust, roof bars, 50 cu m CH_4; *d* — the d25 *Barbara* coal dust, the floor, 50 cu m CH_4; American results: *1* — the dust passes entirely through sieve No. 100, 75% of the dust pass through sieve No. 200; *2* — part of the dust passes through sieve No. 20,40% of the dust pass through sieve No. 200; *3* — part of the dust passes through sieve No. 20, 20% of the dust pass through sieve No. 200; *4* — part of the dust passes through sieve No. 20, 10% of the dust pass through sieve No. 200.

EM Barbara and those obtained by American investigators is quite considerable. On the whole a considerably higher value of W was necessary to prevent a propagation of explosions according to investigations carried out in the *EM Barbara* than according to investigations in the *EM Bruceton.*

Taffanel in his works studies the effectiveness of spraying coal dust with water. But only a small number of his experiments was carried out with coal dust uniformly saturated with water. Using coal containing 32 percent of volatile matter he found that 33 percent of water made coal dust incapable of propagating an explosion. The coal dust used by him was very fine containing 95 percent of fraction < 75 μm. In the case of coal dust containing 37 percent of this fraction 17 percent of water had been found to suffice. These values were found under conditions described as *limit 2* [167]. The values established by Taffanel are much lower than those found in the *EM Barbara.*

British research workers carried out investigations on the effectiveness of combined (crystalline) water [118]. They found that such water is six times as effective as incombustible solid matter in relation to the same quantity of coal dust.

Investigations on the effectiveness of the combined water carried out in the *EM Barbara*, however did not confirm the results obtained by British investigators. Likewise the examination of coal dusts which, in spite of a high content of W_k, retained their dispersibility proved that in such cases combined water is much less effective than water reducing the dispersibility of coal dust.

3.4.10. A mathematical expression of the dependence of W upon the content of incombustible solid matter n in the dust

In accordance with explanations given in Sections 3.4.4 to 3.4.6 in respect of coal dusts containing more than 25 percent of volatile matter the value of W can be determined, approximately, depending upon the contents of incombustible solid matter n on the basis of the diagram given in Fig. 3.15.

The question of the dependence of W upon a series of basic parameters of coal dust is rather complicated but it has been expressed mathematically on the basis of the results obtained experimentally: this matter will be discussed in one of the later chapters. Here, however, it is already possible to introduce an equation describing the dependence of W upon n in respect of the $d85$ coal dust when a very strong explosion initiator is used and the conditions of the dispersion of dust are the easiest. This depend-

ence, for coal containing volatile matter $V > 25$ percent, is described by the following equation

$$W = 0.58(n_0 - n) \tag{3.14}$$

where

W — the content of free water in the dust sufficient to prevent a propagation of an explosion,

n_0 — the content of incombustible solid matter in the given dry dust making the dust incapable of propagating an explosion,

n — the content of incombustible solid matter in the natural dust — that is, in a humid or wet dust.

The formula for finding the value of n as depending upon the basic parameters of coal dust will be given in the chapter in which general formulas are to be discussed expressing conditions making coal dust incapable of propagating explosions. The formula (3.14) can be used without knowing the grain-size distribution assuming the value of n_0 to be equal to the value determined by regulations. According to regulations, binding at the present time in Poland for methane seams, this value can be assumed to be: $n_0 = 80$ percent; while for seams containing no methane and for methane seams classified to the I category of the gas hazard $n_0 = 70$ percent.

Thus, knowing only the content of incombustible solid matter in the humid (natural) dust it is possible to find the value of W. It will give a serious safety margin.

The formula (3.14) deserves to be introduced here as an uncommonly simple means of finding the value of W, with a large safety margin, when only the content of incombustible solid matter n in the natural — that is, humid dust is known and this content can always be found very easily in a laboratory by making a single analysis.

3.4.11. General information about the hazard of wet coal dust explosions in mines

The results of the investigations, taken in their entirety, show that — when explosion initiators are strong — high contents of water exceeding the absorption capacity of the dust are necessary in order to protect pure coal dust against the propagation of explosions. When the initiators are weak considerably smaller quantities of water suffice to produce the same result. These facts are of great importance to the mining practice.

Strong explosion initiators occur in mines much less frequently than weak initiators.

The most common initiator of coal dust explosions is the explosion of firedamp. In methane seams large accumulations of the explosive mixture of methane occur much less frequently than small local accumulations. The hazard of long firedamp zones exists in seams in which squealers and outbursts occur more or less frequently and, in general, in seams that are strongly methane when there is a fault with, or a breakdown of, the ventilation system. Under such conditions the probability of explosions increases in the zones of humid or even wet coal dust affected by strong firedamp explosions. Coal dust in mines rather seldom corresponds to the so-called $d85$ type; it is usually more akin to the $d25$ dust.

Coal dust in mines usually contains large quantities of incombustible solid matter. The distribution of mine dust in workings is, as a rule, less favorable to dispersion than the easiest dispersion conditions prearranged for experiments.

Taking into account the above considerations it can be concluded that the contents of water sufficient to protect mine dust against the propagation of explosions — even in the face of a very strong initiators — are usually much lower than the maximum contents found in the described investigations.

It would not be proper to omit in our considerations the question of the big difference existing between conditions under which investigations are carried out and conditions prevailing in mines where wet coal dust is found. In the investigations only the mass of the examined coal dust was saturated with water, while the surface of the experimental gallery remained relatively dry. In mines, the surface of workings in which wet coal is found is either humid or wet. At the time of an explosion this surface cools the flame and thus makes the propagation of the explosion difficult.

Here it should be emphatically stated that zones with fine, pure and dry coal dust create a great hazard of becoming a strong initiator, especially when such zones begin directly at the place where an explosion is being initiated or are situated near to such a place. When such zones are contiguous to zones containing humid or wet dust, an explosion can develop also in these zones with humid or wet dust causing a great disaster.

The fact that humid or wet coal dust can, under the impact of a strong initiator, produce a violent explosion is a fact of great importance. It shows that water, all things considered, is not as reliable a protection against the propagation of coal dust explosions as a high content of incombustible solid matter in the dust. In the use of water as a means of making mine dust safe a tremendous role is played by the stability of the wet conditions of the workings. If these conditions are changeable one cannot rely on the wetting of the dust as a constant factor.

The gist of the above considerations is that, when the protection of coal dust through water is being considered, attention should be paid, in particular, to the question whether the zones containing wet coal dust are not adjoining zones which can possibly become zones of a strong explosion initiator.

The remarks given above supplement the data gathered from coal dust explosions in mines. While the quantitative data on coal dust explosions is relatively modest yet there is a certain eloquence in the fact that in Polish mines no case is known of an explosion of coal dust under conditions of a high natural humidity of this dust.

In order to avoid any misunderstanding note that the above remark is correct in reference to such humidity conditions when the entire coal dust accumulated in the relevant workings is saturated with water to the point at which it loses completely its dispersibility and when surface layers of dispersible coal dust are quite absent.

In seams both containing and not containing firedamp the danger of the explosion of humid, and even wet, coal dust becomes real when on the surface of the accumulated dust, layers of a dispersible pure coal dust are present.

In other countries, however, there were explosions of humid coal dusts in mines as, for example, the explosion in the year 1946 in the American *Centralia* mine [79] and in the year 1957 — the explosion in the Scotch *Kames* mine [145].

When one is acquainted with the question of the explosibility of humid or wet coal dust it is possible to find out in natural conditions whether the danger of this kind actually exists. For this danger depends upon the probability of the occurrence of a strong explosion initiator. In the case of a seam containing no firedamp, and when there are no accumulations of dry fine coal dust, it is possible to assume that an explosion of wet coal dust can take place only in consequence of a strong explosion of flammable fire gases. In the case of a methane seam, on the other hand, especially when there are zones of dry fine coal dust, the possibility of an explosion of even very wet coal dust cannot be excluded.

The question whether a particular seam contains firedamp is usually settled in the classification of the seam by mining authorities. The accumulation of dangerous, fine, pure, dry coal dust is easy to detect and this applies also to the deposits of such coal dusts on the wet or humid dust. In summing up it can be said that an adequate knowledge of the principles of (the reasons for) the explosibility of wet coal dust makes possible the evaluation of the reality of the danger it carries to mining operations.

3.5. THE EFFECT OF THE TIME OF DEPOSITION OF COAL DUST ON ITS EXPLOSIBILITY

3.5.1. General information

All investigations described in the present book were carried out with the use of coal dust being stored, on the average, approximately a month before the experiments were made. Under the ordinary conditions in mines, at farther distances from the front of mining operations, coal dust is found a big part of which might have been lying deposited a long time. In connection with this fact the explosibility has been investigated of coal dust lying in deposits a relatively long time.

To this purpose the standard dust from the *Barbara* seam, d25 and d85, was used which had been kept in a normally aired storehouse for a period of four years, counting from the time when the coal was ground to the time when experiments were made, in order to establish the explosibility of the dust.

In order to establish the explosibility of coal dust accurately a large number of experiments on a large scale must be carried out. On account of local difficulties it was not possible to keep in store over such a long period of time the quantities of coal dust sufficient for making numerous experiments, particularly because the experiments were carried out in a gallery 400 m long. In consequence only approximate results were obtained which determine the explosibility of the dust in question.

In view of the fact that the influence of a change of conditions prevailing in the experimental gallery had to be taken into consideration experiments were carried also, in the same period of time, on the explosibility of fresh coal dust. This procedure was necessitated in particular by the fact that at the time when experiments were being conducted with coal dust lying in deposits a long time the experimental gallery was humid.

In the experiments the initiator 30mPII was used and the easiest conditions of dispersion were prearranged.

3.5.2. Investigations on the explosibility of the d25 coal dust after four years of storage

Only four experiments were carried out in this case. On the basis of these experiments it was established approximately that the minimum content of incombustible solid matter in the dust, sufficient to make it incapable of propagating an explosion along the 400 m zone, amounted to: $S = 57.5$ percent.

Comparative experiments carried out in the same period of time indicated, with an analogous degree of probability, that the explosibility of freshly prepared $d25$ coal dust from the same seam is characterized by $S = 62.5$ percent. A comparison between the values of S established for the two kinds of the examined coal dust proves that storing of the dust for a period of four years reduces the explosibility of coal dust but slightly.

It is worth mentioning that, according to Table 6.10, the value of S for $d25$ coal dust, found under the same conditions with a probability index $P = 10^{-2}$, amounted to $S = 65.5$ percent.

3.5.3. Investigations on the explosibility of the $d85$ coal dust after four years of storage

Only five experiments were carried out with $d85$ coal dust. As the result of these experiments the approximate value of S was found to be 70 percent. Comparative experiments carried out with freshly ground $d85$ coal dust resulted in establishing, with an analogous degree of probability, the value of $S = 75$ percent.

Thus the explosibility of $d85$ coal dust after four years of storage becomes lower also in a relatively insignificant measure.

According to Table 6.10 the value S for $d85$ dust, established under the same conditions with the probability $P = 10^{-2}$, amounted to $S = 79.5$ percent.

It should be stressed that the results given above of the investigations on the explosibility of coal dust which was kept stored for a period of four years are only approximate. Indeed, for accurate establishment of the influence of the storage time on the explosibility of this dust much more numerous experiments are necessary which would allow statistical analysis of the results obtained.

4. LIMIT EXPLOSIBILITY OF COAL DUST AND ITS DEPENDENCE UPON THE BASIC PARAMETERS

4.1. GENERAL INFORMATION

An important role in the problem of the explosions of gases is played by limit explosibility of mixtures of inflammable gases with air.

To the basic data in this respect belong the lower and upper litmit explosibility. The significance of this data is obvious and, therefore, the limit explosibility of every inflammable gas, especially of gas technically important, is well known. Analogously, in the problem of coal dust explosions the limit explosibility of the dust is of paramount significance. The most important — from the practical point of view — is the lower limit of the coal dust explosibility.

Despite the fact that this problem is very important much less attention was paid to it in research works carried out throughout the world than to the problem of the explosibility of gases. Though basic laboratory researches were made, as mentioned already in Section 2.2, yet they were rather few and were confined chiefly to the determination of the lower limit explosibility of coal dust. In the practice of mining, of course, it is not important to know the minimum quantity of coal dust capable of propagating an explosion on the scale of a mine.

Still fewer investigations were carried out on the upper limit explosibility of concentrations of coal dust and the absence of accurate data is observed in this field more clearly. The reason for such an attitude of investigators to this problem is relatively simple. Investigations on the explosibility of coal dust carried out on a mine scale already in their initial stages have proved (Taffanel 1910–1912) that the quantities of dust sufficient to propagate explosions are quite small and practically always considerably smaller than the quantities of coal dust deposited, on the average, in mine workings. Moreover, it has been established in experimental galleries that explosions of coal dust can be propagated even in such cases in which the degree of the concentration of the dust is very high. It was concluded, therefore, that the quantities of dust which one finds as a rule in mines, various as they are, are usually within the limit explosibility.

The fundamental means of preventing the danger of firedamp explosions consists in the removal of firedamp and in the reduction of its concentration through ventilation. In the suppression of coal dust explosions an analogous procedure is extremely difficult to adopt in practice. The quantities of mine dust sufficient to propagate explosions are usually smaller than 100 g/cu m, while the quantities of the dust found in mine workings are much greater than that, as a rule. In the practice of mining it is very difficult to remove coal dust to such an extent that the quantities left would be below the lower limit explosibility.

Nevertheless, the knowledge of the limit explosive concentrations of coal dust is of basic importance in all of the fundamental problems of the explosibility of coal dust. Moreover, the lower limit explosibility of coal dust is of particularly great consequence in the evaluation of conditions in which clouds of coal dust, occurring in special circumstances in mines, become dangerous. This applies, for instance, to the mining of coal by mechanical equipment.

Investigations on the limit quantities of coal dust may be divided into two principal groups:

— investigations carried out on a laboratory scale (discussed in Section 2.2),

— investigations carried out on a scale approaching actual conditions existing in mines.

Laboratory investigations deal with the development of the flame in a cloud of dust produced intentionally which we are going to call in short: the primary cloud because the phenomenon of the development of the flame in this cloud corresponds to that occurring in the primary cloud defined in Section 1.3. Here, the question whether the development of the flame in this cloud will eventually, or will not, create a blast sufficiently strong to raise secondary clouds capable of propagating the explosion, is disregarded entirely.

The limit concentrations at which the flame can develop in the primary cloud should be differentiated from the limit concentrations of the dust sufficient to make the propagation of an explosion possible. These two values are of very special practical importance to the problem of coal dust explosions in mines.

The data in the literature on this subject refers to either the first or the second of the two notions. When these two notions are not strictly discerned misunderstandings are bound to occur.

The above two different meanings of the limit explosive concentrations of coal dust will be referred to, in short, in the further text as the limit quantities:

— for the primary cloud,

— for the propagation of explosions.

The limit explosive concentrations of coal dust will be denoted by the following symbols:

q_m — the concentration of coal dust at which explosions can be propagated sometimes; the symbol q_m denotes the lower limit value of the explosive concentration of coal dust;

q_0 — the concentration of coal dust at which in no case a propagation of an explosion will occur; the accuracy of the value of q_m is determined by the difference between q_m and q_0 and by the number of experiments performed;

q_p — the concentration of coal dust at which a propagation of an explosion occurs every time;

q_{opt} — the optimum concentration of coal dust at which an explosion achieves the maximum velocity; in other words, the concentration at which the explosion is the most violent; q_{opt} is not determined normally for pure coal dust because the violence of an explosion of such a dust might damage the experimental equipment, but the determination of q_{opt} is commonly carried out when investigating the degree of the explosibility of coal dust by the method of finding out the quantities of incombustible solid matter necessary to make the propagation of an explosion impossible; this may be expressed by the symbols used in the discussion of the explosibility of coal dust in the following manner: q_{opt} occurs when $n = S$;

Q_0 — the maximum concentration of coal dust at which a propagation of an explosion was not observed;

Q_m — the concentration of coal dust nearest to Q_0 at which a propagation of explosions still occurred at times; this is the upper limit explosibility of coal dust.

All of the above enumerated values can be converted to values representing d.a.f. carbon substance. In such cases the relevant symbols are marked with the index w.

In a manner analogous to that of finding the value of q_p it is possible to find the value of Q_p — that is, the maximum concentration of coal dust at which the propagation of explosions occurs invariably. The value of Q_p, for pure coal dust, has not been determined.

All the definitions given above refer to the limit concentrations of coal dust connected with the phenomenon of the propagation of explosions. Moreover, and this should be emphasized, the concentrations in question represent the quantities of coal dust deposited in an experimental gallery which means that they refer to the quantities of the dust per unit of volume. Obviously this has a practical significance since in exactly the same manner the concentration of coal dust accumulations in mine workings is determined.

These quantities obviously do not correspond to concentrations of coal dust in a cloud in which a flame develops. During an explosion the pressure in the explosive medium is always higher than the atmospheric pressure. Should one even assume that the dust was quantitatively uniformly dispersed throughout the cross section of the gallery, the real concentration of the dust must be higher than that which would have been found through dividing the quantity of the dust by the volume of the space in which it had been deposited. The pressure of the explosion brings about a growth in the density of the gaseous medium (the air) and this, in its turn, must increase the concentration of the dust per unit of volume. This real concentration of the dust is not known, yet it can be determined approximately by measuring the pressure in the zone of the explosion and assuming that the entire quantity of the dust deposited in the underground experimental gallery had been raised to the air and uniformly dispersed in it

4.2. RESULTS OF INVESTIGATIONS ON THE LOWER LIMIT EXPLOSIVE CONCENTRATION OF PURE COAL DUST

4.2.1. The results of investigations and general information

Many research workers carried out work on the determination of the lower limit explosive concentration of coal dust q_m. The results of their work are given in Table 4.1. They depend very markedly upon the kind of the coal dust and the degree of its fineness, on the dimensions of the experimental galleries, on the explosion initiator and — by and large — on the conditions in which experiments are carried out and on the number of experiments.

The majority of the examined coal dusts closely resembles each other as far as their contents of volatile matter are concerned. This makes the comparison of the results quite satisfactory. For coal dusts similar to each other, with closely approximate degree of fineness, the value of q_m oscillated between 50 and 112 g/cu m. Thus, the differences are very big.

In the *EM Barbara* [28] 372 experiments were carried out in which the most meticulous care was taken to secure a distribution of coal dust ensuring its possibly most uniform dispersion in the cross section of the surface and underground galleries. In Polish experiments coal dust had been deposited on laterally placed boards which were thrown down during the explosion. In this way, with a strong explosion initiator, the best possible dispersion of coal dust was ensured in the entire cross section of the gallery.

Table 4.1

Results of Investigations on the Lower Limit Concentrations of "Pure" Coal Dust Capable of Propagating Explosions

Investigators (Institutions)	Volatile matter V %	Fineness of coal dust	Explosion initiator	Gallery: underground cross section area sq m	Gallery: surface length m	Number of experiments	q_m g/cu m
Taffanel (*Lievin*)	30	< 66 μm	240 g	2.8	65		112
	30	90%	of explosive	2.8	65		225
	24	50%	gelatine	2.8	65		225–337
		90%					
Rice (*Bruceton*)	30	< 74 μm 80%					80
Levitski and Chernitsyn (*Makeevka*)							30–40
Wheeler Mason (*Buxton*)	35.9	<76 μm 85%	567 g of black powder	1.13	100	3	75
Cybulski 1930 (*Barbara*)	30	<75 μm 90%	250 g of explosive gelatine	3	44	10	70
	30	50%	250 g of explosive gelatine	3	44	10	100
	30	23%	250 g of explosive gelatine	3	44	10	250
Cybulski 1954 (*Barbara*)	38.3	powder 100% <75μm	10 cu m CH_4	3	100	36	45
	41.5	85%	10 cu m CH_4	3	100	32	50
	42	25%	10 cu m CH_4	3	100	36	125
	28.1	85%	10 cu m CH_4	3	100	33	150
	18.3	85%	10 cu m CH_4	3	100	15	150
	40.8	85%	50 cu m CH_4	5	200	19	60
	41.2	25%	50 cu m CH_4	5	200	22	75

How important to the task of determining the limit concentrations of coal dust is the manner in which the dust is distributed may be illustrated by the following example: when the d23 coal dust had been deposited on the floor of the experimental gallery the value of q_m was found to equal 2 kg/cu m, while the same kind of dust deposited on roof bars produced the value of q_m equal to 150 g/cu m. It should be noted that in these experiments — just as in all other experiments carried out for the purpose of determining limit concentrations of coal dust in the underground experimental gallery — the initiator 50 cu m CH_4 had been used.

The differences which are due to the characteristics of surface experimental gallery and to the kind of the initiator used are best illustrated

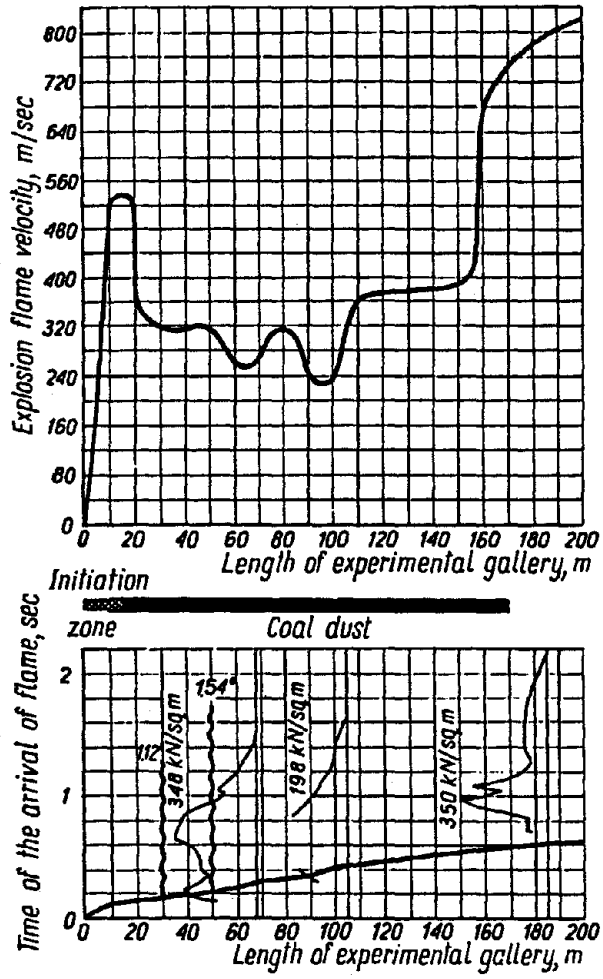


Fig. 4.1. A diagram of explosion No. 2217 in the 200 m experimental gallery: the d25 *Barbara* dust, F = 1350 (2350) sq cm/g, V = 41.2%, q_m = 75 g/cu m, $q_{m\,w}$ = 66 g/cu m, initiator 50 cu m CH_4 9.5%.

Table 4.2

Limit Explosive Concentration of Coal Dust Found in the Surface Experimental Gallery of the *EM Barbara*

Seam	Volatile matter content V, %	Contents in the dust of fraction <75 μm %	Specific surface of the dust F, sq cm/g	The limit concentration of the dust (kg/cu m) and the surface of the limit concentration of the dust (sq m)				
				q_o q_{ow} f_{ow}	q_m q_{mw} f_{mw}	q_p q_{pw} f_{pw}	Q_m Q_{mw}	Q_o Q_{ow}
Barbara	41.5	85	2400 (4200)	0.045 0.038 15.96	0.050 0.041 17.22	0.075 0.065 27.3	0.80 0.68	0.90 0.77
	38.3	100 (powder)	10,900 (19,100)	0.040 0.034 64.94	0.045 0.038 72.58	(0.070) (0.058)	0.90 0.71	1.00 0.82
	42.0	25	1250 (2200)	0.100 0.086 18.92	0.125 0.108 23.76	0.225 0.190 41.8	0.90 0.76	1.00 0.85
62PŁZ	39.7	91	5300 (9300)	0.050 0.048 44.64	0.055 0.053 42.29	— —	—	—
NR	28.1	85	3700 (6500)	0.125 0.093 60.45	0.150 0.111 72.15	—	0.90 0.67	1.00 0.74
2/BC	18.3	85	4900 (8600)	0.125 0.111 95.46	0.150 0.133 114.38	—	0.90 0.80	1.00 0.88

by the results obtained in the *EM Barbara* in which for coal dusts closely similar to each other, in experiments carried out under three different conditions, the following values of q_m were found: in the surface experimental gallery with the explosion initiator consisting of 250 g of explosive gelatine the value of $q_m = 70$ g/cu m; in the surface experimental gallery with the initiator 50 cu m CH_4 — $q_m = 50$ g/cu m; in the underground experimental gallery of 5 sq m cross section area with the initiator 50 cu m CH_4 — $q_m = 60$ g/cu m. Very characteristic is the small difference between the result obtained in the surface experimental gallery and that obtained in the underground experimental gallery with the use of the methane initiator: it shows that in the underground experimental gallery, in spite of its different cross section size, a sufficiently uniform dispersion of coal dust was secured. Nonetheless for the purpose of determining the

limit concentrations of coal dust the most suitable are surface experimental galleries of circular cross sections as under such conditions the most uniform dispersion of coal dust can be obtained. As an illustration of the tests included in Table 4.1, Fig. 4.1 presents a diagram of the d25 *Barbara* coal dust explosion effected in the 200 m experimental gallery with $q_m = 75$ g/cu m. As it can be seen from this diagram the propagation of this explosion was very certain in spite of the low concentration of the dust.

The results of tests made in the *EM Barbara* to ascertain the limit (lower and upper) concentrations of pure coal dust are listed in Table 4.2.

4.2.2. The dependence of q_m and q_{mw} upon the content of volatile matter V

The values of q_m found in experiments conducted in a surface experimental gallery for coal dusts containing from 41.5 to 18.3 percent of volatile matter V show that with the decline in the V index the values of q_m increase from 50 to 150 g/cu m. These values, computed with reference to the d.a.f. coal substance q_w, amount to from 41 to 133 g/cu m.

Coal dusts used in the above experiments varied in respect of their specific surface values which were from 4200 to 8600 sq cm/g. However, this fact had no appreciable influence on the established values of q_m.

Figure 4.2*a* shows the dependence of q_{mw} and q_{ow} upon V.

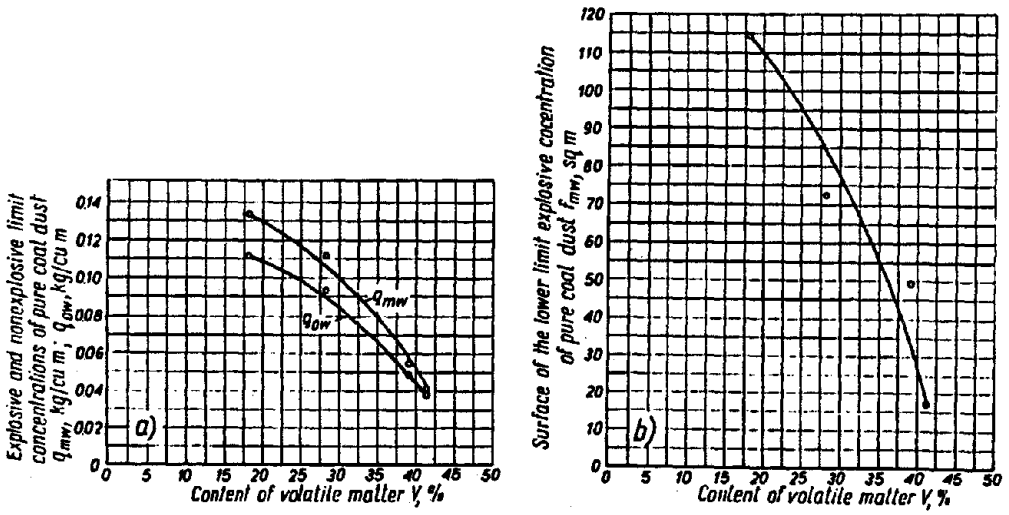


Fig. 4.2. Diagrams of the dependence: a — of the lower limit explosive concentration of pure coal dust q_{mw} and q_{ow} upon the content of volatile matter; b — of the surface of the lower limit explosive concentration of pure coal dust f_{mw} upon the content of volatile matter.

4.2.3. The dependence of q_m and q_{mw} upon the fineness of the dust determined by the specific surface F

It was established that the value of q_m decreases with the increase in the specific surface F only to a certain point beyond which the changes are very slight, for instance, when F increased from 2200 to 4200 sq cm/g, q_m decreased from 125 to 50 g/cu m, but with the further increase in F — up to 19,100 sq cm/g — the value of q_m decreased to only 45 g/cu m. This was the lowest limit explosive concentration of the dust established in the course of the experiments discussed here. The value in question, calculated with reference to pure coal substance $q_{mw} = 38$ g/cu m.

In Fig. 4.2*b* the dependence is shown of the surface f_{mw} corresponding to q_{mw} upon V ($f_{mw} = F \cdot q_{mw}$).

4.2.4. Comparison between the results of investigations carried out in surface and underground experimental galleries

For coal dust of a high degree of fineness (*d*85, $F = 4200$ sq cm/g) the value of q_m established in the underground experimental gallery differed very slightly from that established in a surface experimental gallery. In the underground experimental gallery $q_m = 60$ g/cu m which exceeds only by 10 g/cu m the result obtained in the surface gallery. However, examining coal dust of a lower degree of fineness (*d*25, $F = 2350$ sq cm/g) the value of q_m was found to be 75 g/cu m in the underground gallery — that is, lower than in the surface gallery where $q_m = 125$ g/cu m. This result was unexpected and can be explained by the fact that a stronger initiator had been used and better conditions of turbulence prevailed in the underground gallery.

4.3. THE DEPENDENCE OF THE LOWER LIMIT EXPLOSIVE CONCENTRATION q_m AND q_{mw} OF THE *d*85 COAL DUST UPON THE CONTENT OF INCOMBUSTIBLE SOLID MATTER n

4.3.1. General information

The problem of the dependence of the lower limit explosive concentration of coal dust upon its content of incombustible solid matter is one of the fundamental problems. Apart from its scientific importance this problem is of an equal consequence from the practical point of view because, in mines, one has to do in the majority of cases with mixtures of the seam coal dust with incombustible solid matter.

For the purpose of investigating this dependence, 174 experiments were carried out in two underground galleries one of which was 200 m long, with the cross section area of 5 sq m, and another 400 m long with the cross section area of 7.5 sq m. Besides, the results of investigations described in Sections 4.1 to 4.3 were taken into consideration.

In order to obtain data corresponding to actual conditions in mines the investigations were carried out on the scale of mine workings.

The main subject of the examination had been the manner in which the concentration of the carbon substances q_{mw} in relation to the increase in the concentration of incombustible solid matter q_n increased with the increase in the content of incombustible matter n in the dust.

To secure the best possible dispersion of the dust in the entire cross section of the underground galleries, the initiator used in the 200 m gallery had been 50 cu m of an explosive mixture of methane containing from 8 to 9.5 percent of CH_4; in the 400 m gallery — 100 cu m of the same mixture. It should be pointed out that the range of the flame of an explosion of 50 cu m CH_4 in the 200 m gallery was, on the average, about 55 m; that the average maximum velocity of the flame amounted to 380 m/sec; and that the maximum static pressure was 2.05 kg/sq cm. The range of the flame of an explosion of 100 cu m of methane in the 400 m gallery was, on the average, about 75 m; the average maximum velocity of the flame was about 520 m/sec and the maximum pressure averaged about 275 kN/sq m. All tests were made with the *d*85 *Barbara* dust.

The influence of limestone dust and of clay-slate dust on the value of q_m. Mine dust contains, as a rule, incombustible solid matter consisting of ash from coal, of clay slates from the roof and floor rocks and of limestone dust with which workings are dusted.

It was necessary to find out whether limestone dust and clay-slate dust influence the value of q_m differently.

Tests carried out under various conditions testified that equal contents of either of the above gangue dusts exert an equal influence upon the value of q_m.

4.3.2. Results of investigations in the 200 m underground gallery

In the tests in question pure coal dust was used with the natural content of incombustible solid matter amounting to 13 percent, and also coal dust with the content of n equal to 50, 60, 70, 77.5 and 80 percent. The results are listed in Table 4.3 in which limit concentrations of the dust q_m are given in g cu/m for mixtures of coal dust with limestone dust and for d.a.f. carbon substance q_{mw}. The figure 200 given with the values of q indicates that the tests were made in the 200 m gallery.

Table 4.3

Dependence of the Limit Explosive Concentration of Coal Dust upon the Content of Incombustible Solid Matter n (investigations carried out in the 200 m gallery; the $d85$ *Barbara* coal dust and the 50 cu m CH_4 initiator were used)

Incombustible matter content n, %	Dust concentration, g/cu m					
	q_{0200}	q_{0w200}	q_{m200}	q_{mw200}	q_{p200}	q_{pw200}
13	50	42	60	52	70	63
50	100	50	125	62.5	175	87.5
60	150	60	175	70	200	80
	150	60	175	70	200	80
70	200	60	250	75	300	90
	200	60	250	75		
77.5	400	90	500	112.5		
80	750	150	1000	200		

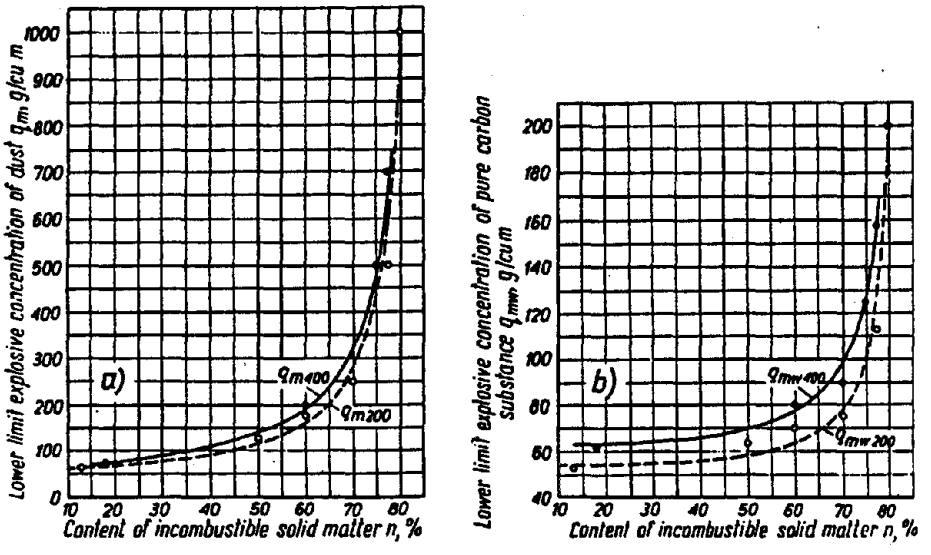


Fig. 4.3. Diagrams of the dependence of the lower limit explosive concentration: *a* — of the q_m dust upon the content of incombustible solid matter n in the mixture of the $d85$ *Earbara* coal dust with limestone dust determined in the 200 and 400 m galleries according to equations (4.1) and (4.3), ● ——— — 400 m gallery, o - - - — 200 m gallery; *b* — of the pure carbon substance q_{mw} upon the content of incombustible solid matter n in the mixture of the $d85$ *Earbara* coal dust with limestone dust determined in the 200 and 400 m galleries according to equations (4.2) and (4.4), ● ——— — 400 m gallery, o - - - — 200 m gallery.

The values of q_m found through these tests were marked in the graph shown in Fig. 4.3*a*. Employing the method of the least squares the following equation of the hyperbola was found

$$q_{m\,200} = \frac{3384.4}{83.3 - n} + 14.4 \tag{4.1}$$

The curve representing the dependence of $q_{m\,200}$ upon n, as shown in Fig. 4.3*a*, corresponds sufficiently well to the marked results of the tests carried out.

The values of $q_{mw\,200}$ found in the same way were marked in the graph shown in Fig. 4.3*b*. Employing the method of the least squares the following equation of the hyperbola was found

$$q_{mw\,200} = \frac{343.0}{82.3 - n} + 48.3 \tag{4.2}$$

In this case also the curve representing the dependence of $q_{mw\,200}$ upon n, as shown in Fig. 4.3*b*, corresponds sufficiently well to the results of tests marked in the graph.

Thus through the tests carried out in the 200 m gallery, the functional relation was established between the lower limit explosive concentration of coal dust and the content of incombustible solid matter.

The curve representing the values of $q_{m\,200}$ (Fig. 4.3*a*) has a very characteristic shape. In the interval between pure dust and the dust containing incombustible solid matter $n = 50$ percent, the increase in the values of $q_{m\,200}$ is very slow. Only when the content of n grows over 50 percent the value of $q_{m\,200}$ begins to rise more quickly and — when n is over 70 percent — this rise becomes very sudden.

The curve representing the values of $q_{mw\,200}$ (Fig. 4.3*b*) has a similar shape. The concentration of the pure carbon substance $q_{mw\,200}$ shows a relatively insignificant rise in the range from pure coal dust to $n = 50$ percent, while this rise becomes very abrupt when $n > 70$ percent.

4.3.3. Results of investigations in the 400 m underground gallery

The results of investigations carried out in the 400 m gallery are particularly valuable since — given such a long zone — it is possible to study the development of an explosion of coal dust when the explosion "develops by itself" — that is, after the impact of the initiator fades away. The tests were made with the same coal dust that had been used in the tests carried out in the 200 m gallery. Pure d85 coal dust was used containing this time $n = 18.2$ percent, and also coal dust with the content $n = 80$, 70, 75 and 77.5 percent.

The results are listed in Table 4.4. The values found through these tests are marked in the graph shown in Fig. 4.3*a*.

Employing the method of the least squares the following equation of the hyperbola was found

$$q_{m\,400} = \frac{4200.4}{83.6-n} + 11.5 \tag{4.3}$$

The curves representing the dependence of $q_{m\,400}$ upon n corresponds sufficiently well to the results of tests plotted in the graph.

Table 4.4

Dependence of the Limit Explosive Concentration of Coal Dust q_m and q_{mw} upon the Contents of Incombustible Solid Matter n (investigations carried out in the 400 m gallery; the *d*85 *Barbara* coal dust and the 100 cu m CH_4 initiator were used)

Incombustible matter content n, %	Lower limit explosive concentration of the dust q_m and q_{mw}, g/cu m			
	200 m zone		400 m zone	
	$q_{m200/400}$	$q_{mw200/400}$	q_{m400}	q_{mw400}
18.2	70	57.26	75	61.35
60	150	60	200	80
70	200	60	300	90
75	400	100	500	125
77.5	600	135	700	157.5

The values of $q_{mw\,400}$ found in the tests are marked in the graph shown in Fig. 4.3*b*. Employing the method of the least squares the following equation of the hyperbola was found

$$q_{mw\,400} = \frac{547.8}{82.8-n} + 53.0 \tag{4.4}$$

In this case also the curve representing the dependence of $q_{mw\,400}$ on n, as shown in Fig. 4.3*b*, corresponds sufficiently well to the plotted results of tests.

4.3.4. Comparison of the results of investigations on the q_m and q_{mw} obtained in the 200 m gallery with those obtained in the 400 m gallery

The hyperbolas shown in Fig. 4.3*a*, representing the values of $q_{m\,200}$ and $q_{m\,400}$, are more or less parallel and the distance between them is relatively small.

The shape of the curves is very charateristic.

In the interval from pure coal dust to coal dust containing incombustible solid matter n equal to approximately 50 percent the rise of the q_m is very slow and begins to be quicker only when the content of n is higher than 50 percent. When this content exceeds 70 percent the rise of the q_m becomes quite abrupt.

Despite the closeness of the curves representing $q_{m\ 200}$ and $q_{m\ 400}$ the distance between these curves, changing very little at first, becomes more and more marked as the content of n increases.

The hyperbolas $q_{mw\ 200}$ and $q_{mw\ 400}$ shown in Fig. 4.3*b* are more distant from each other than the curves in Fig. 4.3*a*.

This, however, is due to the difference in the scale employed for the q_{mw} ordinate. The curves have the shape quite analogous to that of the curves in Fig. 4.3*a*. Therefore, the remarks made above with reference to the curves shown in Fig. 4.3*a* apply equally to the curves in Fig. 4.3*b*.

It is obviously quite understandable that, with the increase of n in the dust, the concentration of the pure carbon substance q_{mw} in a cloud capable of propagating an explosion must increase because a greater quantity of energy, produced by the combustion of coal dust, is needed to propagate an explosion in a cloud containing a higher percentage of incombustible solid matter. Moreover, as was established by the examination of the coke residue in the dust after explosions, the percentage of coal dust grains participating in an explosion decreases as the percentage of n increases. Turning back again to the comparison between the graphs shown in Figs. 4.3*a* and 4.3*b* note that, just as was the case with the curves representing q_m, the differences between $q_{mw\ 200}$ and $q_{mw\ 400}$ increase in the same way with the increase in the percentage of n which is explained by the functional relation between q_m and q_{mw}.

4.3.5. Comparison of q_m and q_{mw} values obtained in underground galleries of different cross section areas

A comparison between explosive concentrations, found with regard to zones of equal length — that is, with regard to the length of 200 m in both the 200 m and 400 m galleries, has been indicated on account of the different cross section areas of these galleries, namely, 5 and 7.5 sq m. The symbol $q_{m\ 200/400}$ had been used to denote the values of q_m found in the 400 m gallery but only with regard to a zone of 200 m.

The results of these tests were published in a tabulated form in the publication [145]. In Fig. 4.4*a* are plotted the results of pertinent tests of $q_{m\ 200/400}$ carried out in the 400 m gallery for which the following equation of the hyperbola was found

$$q_{m\,200/400} = \frac{2439.9}{81.7 - n} + 31.2 \qquad (4.5)$$

The curve representing $q_{m\,200}$ from Fig. 4.3*a* is included also in Fig. 4.4*a* for the purpose of the intended comparison. One can see that the curves included in Fig. 4.4*a* run quite close to each other so that any differences between $q_{m\,200}$ and $q_{m\,200/400}$ may be regarded as comprised within the limits of the experimental errors. This shows that the increase of the cross section area from 5 to 7.5 sq m did not affect in any appreciable way the lower limit explosive concentration of coal dust. It proves also that appropriate dispersion conditions were duly secured in both galleries.

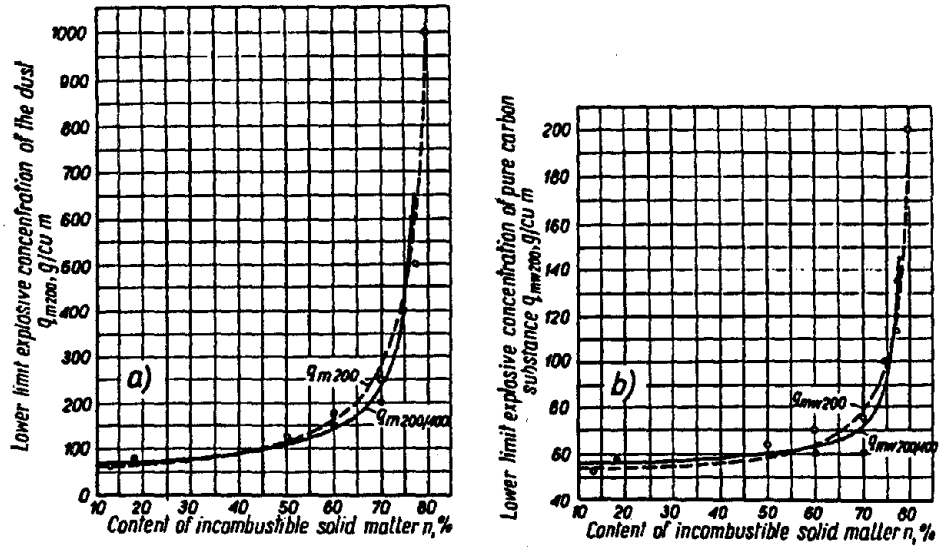


Fig. 4.4. Diagrams of the dependence of the lower limit explosive concentration: *a* — of the q_{m200} dust upon the content of incombustible solid matter n in the mixture of the d85 *Barbara* coal dust with limestone dust determined in the 200 m gallery according to equation (4.1) and along the 200 m zone in the 400 m gallery according to equation (4.5), ● ——— — 200 m zone in 400 m gallery, o - - - - — 200 m gallery; *b* — of the pure carbon substance q_{mw200} upon the content of incombustible solid matter n in the mixture of the d85 *Barbara* coal dust with limestone dust determined in the 200 m gallery according to equation (4.2) and along the 200 m zone in the 400 m gallery according to equation (4.6), ● ——— — 200 m zone in 400 m gallery, o - - - — 200 m gallery.

Similarly the lower limit explosive concentrations of pure carbon substance found in the 200 m gallery — $q_{mw\,200}$ — were compared with those found in the 400 m gallery for a zone of 200 m — $q_{mw\,200/400}$. On the basis of the results of tests carried out in the 400 m gallery in order to

determine the values of $q_{mw\ 200/400}$ an equation of the hyperbola was found

$$q_{mw\,200/400} = \frac{177.1}{79.6-n} + 53.9 \tag{4.6}$$

In Fig. 4.4*b* the curve representing $q_{mw\ 200}$ was again transferred from Fig. 4.3*b* and a hyperbola was plotted representing $q_{mw\ 200/400}$ according to the equation (4.6).

Just as the curves in Fig. 4.4*a*, the curves in Fig. 4.4*b* run very close to each other which shows that the lower limit concentrations of pure carbon substance did not change appreciably with the increase in the cross section area of the gallery.

4.3.6. Comparison of q_m values obtained along 200 and 400 m zones

This comparison is interesting because it concerns the limit explosive concentrations found for zones of different lengths and, moreover, because the tests made in a 400 m zone may be regarded as the more conclusive for the steady propagation of an explosion. All other parameters of the tests remained unchanged.

In Fig. 4.5*a* curves are plotted representing $q_{m\ 400}$ according to the equation (4.3) and $q_{m\ 200/400}$ according to the equation (4.5).

These curves diverge clearly from each other from the point marking approximately a 50 percent content of incombustible solid matter. Analogously in Fig. 4.5*b* curves are set together representing $q_{mw\ 400}$ and $q_{mw\ 200/400}$ taken from Figs. 4.3*b* and 4.4*b*, respectively. Similarly to those shown in Fig. 4.5*a* these curves diverge from each other particularly from the point marking approximately a 50 percent content of incombustible solid matter.

The differences between q_{mw} values found in the 200 m and 400 m zones, with unchanged values of n, are quite comprehensible. The concentration of pure carbon substance in a cloud of its mixture with stone dust must be higher when there is a steady propagation of an explosion than under conditions of a yet unsteady explosion still remaining under the impact of the initiator.

In order to attain conditions of a steady propagation of an explosion, which becomes possible already in a zone 400 m long, a higher concentration of pure carbon substance is necessary than that which will suffice to propagate an explosion through a zone only half so long in which the influence of a strong initiator is still at work.

It is necessary to add that the tests described above confirmed clearly the fact that — when very strong explosion initiators are used — an explosion becomes steady only in the zone over 200 m in length.

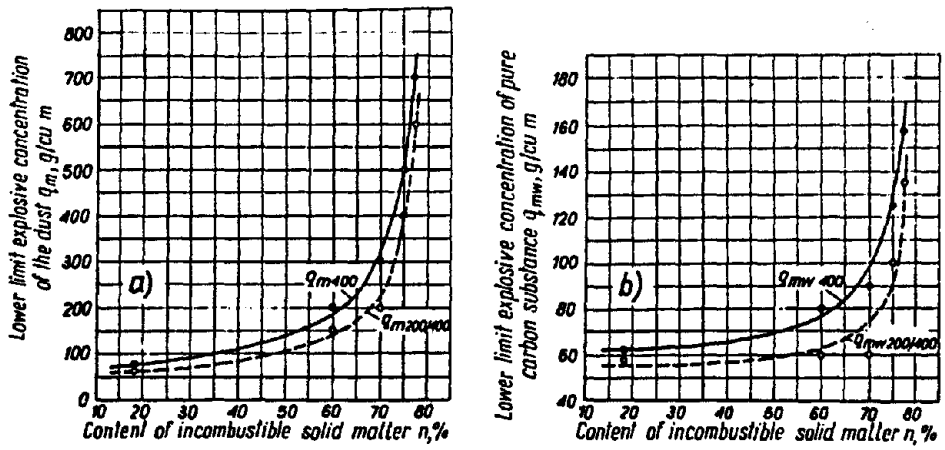


Fig. 4.5. Diagrams of the dependence of the lower limit explosive concentration: a — of the q_m dust upon the content of incombustible solid matter n in the mixture of the d85 *Barbara* coal dust with limestone dust determined in the 400 m gallery along the 400 m zone according to equation (4.3), and in the 400 m gallery along the 200 m zone according to equation (4.5), ● ——— — 400 m gallery, o - - - — 200 m zone in 400 m gallery; b — of the pure carbon substance q_{mw} upon the content of incombustible solid matter n in the mixture of the d85 *Barbara* coal dust with limestone dust determined in the 400 m gallery along the 400 m zone according to equation (4.4), and in the 400 m gallery along the 200 m zone according to equation (4.6), ● ——— — 400 m gallery; o - - - - — 200 m zone in 400 m gallery.

4.3.7. The variability quotients of the increase of incombustible solid matter and of pure carbon substance depending upon the increase of the content of incombustible solid matter in a cloud of a mixture capable of propagating an explosion

The problem set forth in the title of this section is one of a fundamental importance. With the increase in the value of n, obviously, both the concentration of incombustible solid matter in a cloud q_m and the concentration of pure carbon substance q_{mw} also increases.

It is essential to find out whether the relation between the increase in the concentration of incombustible solid matter and the increase in the concentration of pure carbon substance

$$\eta = \frac{\Delta q_{mn}}{\Delta q_{mw}}$$

$$q_{mn} = q_m - q_{mw}$$

does change (or: how it does change) with the increase in the value of n. The experimental data obtained permitted to examine the variability of η.

The magnitude of η represents the effectiveness of coal dust as regards

its ability to propagate an explosion depending on the content of incombustible solid matter n in the dust or, reversing the order of reasoning, η represents the effectiveness of incombustible solid matter in preventing the propagation of a coal dust explosion.

On the basis of calculations presented in the publication [45] the following formulas for η_{lim} are arrived at:

— for a 200 m gallery

$$\eta_{200\,lim} = \frac{8.8(82.3-n)^2}{(83.3-n)^2} \tag{4.7}$$

— for a 400 m gallery

$$\eta_{400\,lim} = \frac{6.7(82.8-n)^2}{(83.6-n)^2} \tag{4.8}$$

In Table 4.5 the calculated values of η_{200} and $\eta_{200\,lim}$ are listed. These values were found through operations involving the values of $q_{m\,200}$ and $q_{mw\,200}$, equalized by the regression curves (4.1) and (4.2), and the limit values of $\eta_{200\,lim}$ computed according to the formula (4.7).

In Table 4.6 the calculated values of η_{400} are listed. These values were found through operations involving the values of $q_{m\,400}$ and $q_{mw\,400}$, equalized by the regression curves (4.3) and (4.4), and the limit values of $\eta_{400\,lim}$ computed according to the formula (4.8).

As can be seen from Table 4.5 the values of η_{200}, calculated for the consecutive magnitude ranges of n, and the limit values of $\eta_{200\,lim}$, calculated for separate values of n, are almost identical up to $n = 70$ percent. Over this value of n the values of η_{200} and $\eta_{200\,lim}$ clearly diverge from each other, the value of $\eta_{200\,lim}$ becoming lower and decreasing markedly with the increase in the value of n.

Table 4.5

Calculated Values of $\eta_{200} = \frac{\Delta q_{mn\,200}}{\Delta q_{mw\,200}}$

Incombustible solid matter content n, %	Values of η_{200} computed for the consecutive intervals of n	Limit values of $\eta_{200\,lim}$ computed for the particular values of n
13	—	8.59
50	8.38	8.29
60	8.08	8.06
70	7.47	7.44
77.5	6.63	5.77
80	4.69	3.81

As can be observed from Table 4.6 the values of η_{400}, calculated for the consecutive magnitude ranges of n, and the limit values of $\eta_{400\,lim}$, calculated for separate values of n, do not differ much but the values of $\eta_{400\,lim}$ are lower.

Table 4.6

Calculated Values of $\eta_{400} = \frac{\Delta q_{mn400}}{\Delta q_{mw400}}$

Incombustible solid matter content n, %	Values of η_{400} computed for the consecutive intervals of n	Limit values of η_{400lim} computed for the particular values of n
18.2	—	6.48
60	6.34	6.16
70	5.96	5.79
75	5.55	5.31
77.5	5.05	4.79

The values of both η_{400} and $\eta_{400\,lim}$ decrease markedly with the increase in the value of n.

Using the formulas (4.7) and (4.8) the values of $\eta_{200\,lim}$ and of $\eta_{400\,lim}$ were found for a series of magnitudes n from 10 to 80 percent. As a result of this it was possible to plot (Fig. 4.6) curves representing the dependence of $\eta_{200\,lim}$ and $\eta_{400\,lim}$ upon n.

These curves are similar in their shapes but the values of $\eta_{400\,lim}$ are clearly lower than those of $\eta_{200\,lim}$ up to the magnitudes of n approaching 80 percent when the values of both become equal to each other.

The differences between $\eta_{200\,lim}$ and $\eta_{400\,lim}$ correspond to those between the curves presented in Fig. 4.3 and are in accord with the interpretation given on that occasion.

In the gallery the values of η along the 400 m zone are lower than they are over the 200 m zone because, for the propagation of a stabilized explosion (along the 400 m zone) — with the increase in the content of n — higher increments in the value of $q_{mw\,400}$ are necessary than the increments in $q_{mw\,200}$. This is quite understandable since a stabilized explosion is no longer supported by the initiator as it develops in a zone beyond the initiator's direct influence.

Both curves, up to about 50 percent content of n, very markedly approximated straight lines. This shows that the relation between the increment in the concentration of incombustible solid matter and the in-

crement in the concentration of pure carbon substance approaches a constant value.

When the value of n exceeds 50 percent the curvature of the line becomes clearly marked and when the value of n comes to about 70 percent and over, the decline in the value of η is already very rapid. This, of course, is in accord with the shape of the curves in Fig. 4.3b and shows that — for the values of n about 70 percent and over — the increase in the concentration of incombustible solid matter must be much more rapid.

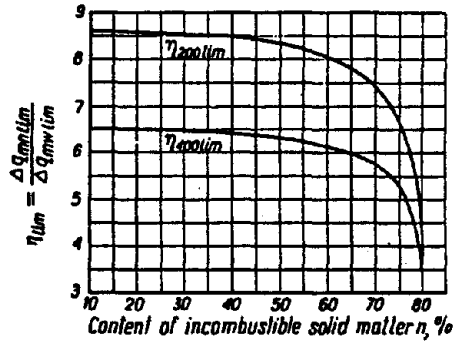


Fig. 4.6. Diagram of the dependence of η_{lim} upon the content of incombustible solid matter n based on the results obtained in the 200 and 400 m galleries according to equations (4.7) and (4.8).

There is a connection between this and the growing difficulty of the propagation of an explosion under the conditions described, which seems to indicate that certain changes occur in the very course of the phenomenon of a coal dust explosion. Research work on this subject is very desirable. The convergence of both values of η, when n has a value approaching 80 percent, may be explained by the fading of the capability of the propagation of an explosion in these mixtures.

4.3.8. Practical conclusions from the investigations on the dependence of the lowest limit explosive concentrations of coal dust upon the content of incombustible solid matter n

Investigations described above, apart from their fundamental worth, have also a direct practical importance.

(1) In order to recognize the hazard connected with any explosive system it is necessary to determine the limit characteristics of its explosibility.

The finding of the dependence between the lower limit explosive concentration of coal dust and the content in it of incombustible solid matter fulfils this basic requirement.

(2) As we know from Section 3.3 in order to prevent the propagation of a coal dust explosion very high contents of incombustible solid matter

are required; sometimes, under special conditions, even in excess of 80 percent. Nevertheless even lower contents of incombustible solid matter, than those required by regulations, are helpful in combating coal dust explosions not only because an explosion of a mixture of coal dust with stone dust is less violent, but also because — as was confirmed by the tests described above — the lower limit explosive concentration increases very materially with the increase above 50 percent of the content of incombustible matter in the dust. As a result with the increase in the content of incombustible matter in the dust the formation of an explosive cloud of coal dust becomes more and more difficult, since it is much easier in practice to raise a cloud of dust of a low concentration, for example, 100 g/cu m, than to raise a cloud of a higher concentration, for example, 300 g/cu m.

In the light of the above remark the statement that — when the content of incombustible solid matter exceeds 50 percent — the values of q_m increase very rapidly is of paramount importance.

(3) In Chapter 4 the upper limit explosive concentration of the dust was not discussed because, as had been explained in Section 4.2, the upper explosive concentration of coal dust is only in a slight measure dependent on the content of incombustible solid matter in the dust.

Taking this fact into consideration it can be stated that the limits of the explosibility of coal dust mixtures with stone dust become narrower with the increase in the content of incombustible solid matter n in the mixture, in particular when the value of $n = 50$ percent.

(4) It ought to be stressed that the above described results of tests refer to the d85 coal dust while the lower limit explosive concentrations are much higher where the more frequently found d25 dust is concerned. This leads to the conclusion that the coarser is coal dust the more difficult it becomes to raise clouds of coal dust of a dangerous explosive concentration.

4.4. THE DEPENDENCE OF THE LOWER LIMIT EXPLOSIVE CONCENTRATION q_m AND q_{mw} OF THE d25 COAL DUST UPON THE CONTENT OF INCOMBUSTIBLE SOLID MATTER n [52]

4.4.1. General information

The tests discussed in Section 4.4 led to the finding of the dependence of q_m and q_{mw} upon n for the d85 coal dust.

Naturally fineness of coal dust in mines varies and, therefore, it was necessary to find the general dependence of the lower limit explosive concentration of coal dust, of any degree of fineness, upon the content of incombustible solid matter n.

The tests were carried out with the *d*25 *Barbara* coal dust. All tests were carried out in the 400 m underground gallery which means that these tests concerned the stabilized development of coal dust explosions. Optimum conditions for the dispersion of coal dust were ensured. Since the comparative tests concerning the length of zones with coal dust and the cross section areas of galleries, described in Section 4.3 for the *d*85 coal dust, were quite adequate no such tests were carried out for the *d*25 dust. As the explosion initiator 100 cu m of an explosive mixture of methane of 9.5 percent CH_4 concentration had been used. Symbols analogous to those used to denote the results of the tests described in Section 4.3 were used also this time, except that the figure 25 was added to the inferior symbols denoting the magnitudes q_m, q_{mw}, q_0 and q_{0w} to mark the difference.

Tests concerning q_{m25} were carried out for the values of n equal to 20, 30, 40, 50 and 60 percent.

4.4.2. The results of investigations on the dependence of q_{m25} upon n

The results of tests concerning q_{m25}, q_{mw25} and q_{0w25} are listed in Table 4.7.

Table 4.7

Limit Explosive Concentration of Coal Dust Depending upon the Content of Incombustible Solid Matter n (investigations carried out along the 400 m zone; the *d*25 *Barbara* coal dust; initiator 100 cu m CH_4)

Incombustible solid matter content n, %	Lower limit concentration of coal dust, g/cu m			
	q_{m25}	q_{mw25}	q_{025}	q_{0w25}
20	115	92	100	80
30	140	98	125	87.5
40	225	135	200	120
50	425	212.5	375	187.5
60	800	320	750	300

The results concerning q_{m25} and q_{mw25} included in Table 4.7 are plotted as points in Fig. 4.7. Regression equations were found expressing the relations between the variables q_{m25}, q_{mw25} and n.

The equations in question have the form

$$q_{m25} = \frac{7885}{69.1 - n} - 50 \tag{4.9}$$

$$q_{mw25} = \frac{3517}{71.9 - n} + 22 \qquad (4.10)$$

In Fig. 4.7 curves are drawn corresponding to equations (4.9) and (4.10).

It may be assumed that the deviations of the points determined through tests from the hyperbolas are comprised within the limits of test errors.

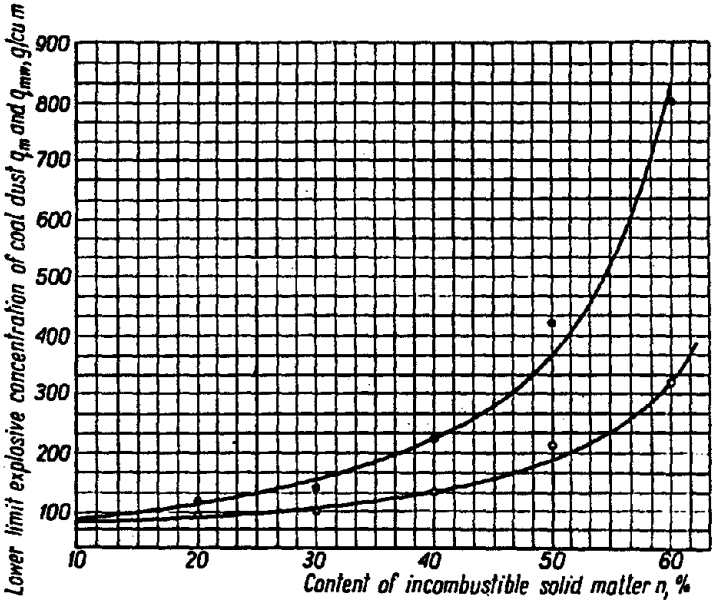


Fig. 4.7. Diagrams of the dependence of the lower limit explosive concentration of the d25 *Barbara* coal dust and q_{m25} and of the pure carbon substance q_{mw25} upon the content of incombustible solid matter n according to equations (4.9) — curve ●●● and (4.10) — curve o o o

4.4.3. Comparison of q_{m25} with q_{m85} at different values of n

Figure 4.8 presents curves illustrating the dependence of q_m upon n for coal dusts $d25$ and $d85$ according to equations (4.3) and (4.9). These curves are also shown in Figs. 4.3*a* and 4.7

As is seen from Fig. 4.8 the fineness of coal dust exerts a very strong influence upon the limit explosive concentration of coal dust. The strength of this influence grows very markedly with the increase in the value of n; for instance, for $n = 60$ percent — $q_{m85} = 200$ g/cu m, and $q_{m25} = 800$ g/cu m.

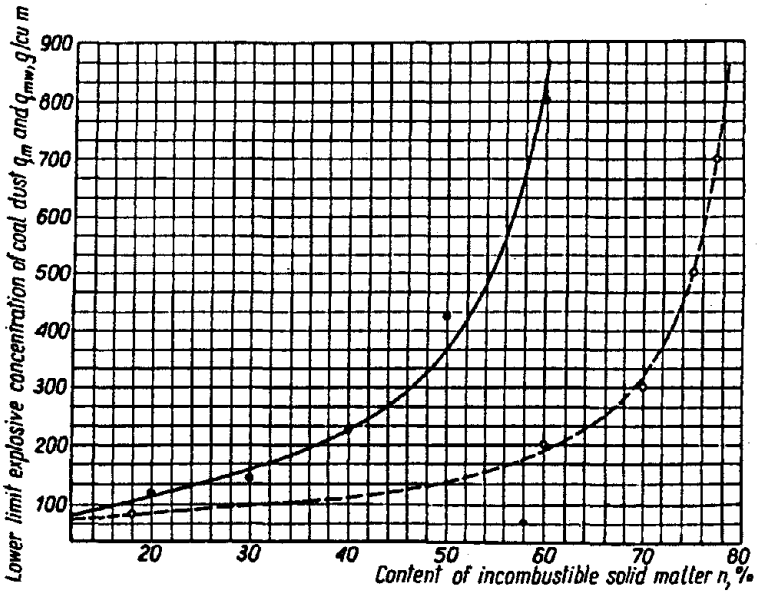


Fig. 4.8. Comparative diagrams of the dependence of the lower limit explosive concentrations q_{m25} and q_{m85} upon the content of incombustible solid matter n according to equations (4.9) — curve ——— ●●●, and (4.3) — curve - - - o o o.

It is a well known fact that the influence of the fineness of coal dust upon its explosibility is very strong. This became manifest also in the research work on the limit explosive concentrations. As an illustration the graph presented in Fig. 4.9*a* shows the velocity of the flame of a *d*25 coal dust explosion where $n = 60$ percent and $q_{m25} = 1200$ g/cu m, and the graph in Fig. 4.9*b* shows the velocity of the flame of a *d*85 coal dust explosion in which $n = 70$ percent and $q_{m85} = 300$ g/cu m. Straight lines of the graphs represent the pertinent velocities of the flame reduced to mean values with the aid of a computer. By comparing the two graphs it is found that there is a very big difference between the velocities of the *d*25 and *d*85 dust. It ought to be stressed here that the *d*85 dust contained 10 percent more of incombustible solid matter than the *d*25 dust. On the other hand the concentration of the *d*25 dust had been four times as high as that of *d*85 dust.

Analogously, in order to compare the limit explosive concentrations of pure carbon substance in coal dusts *d*25 and *d*85 at different values of n, curves were drawn in Fig. 4.10 in accordance with the equation (4.10) for coal dust *d*25, and according to equation (4.4) for coal dust *d*85 and these curves were also shown in Figs. 4.5*b* and 4.7.

The influence of the fineness of coal dust upon the limit explosive concentration of pure carbon substance manifests itself here with partic-

ular clarity. For d85 coal dust — up to about 60 percent content of n — the growth of the value of $q_{m\,ic}$ is very slow while for d25 coal dust this growth is very rapid.

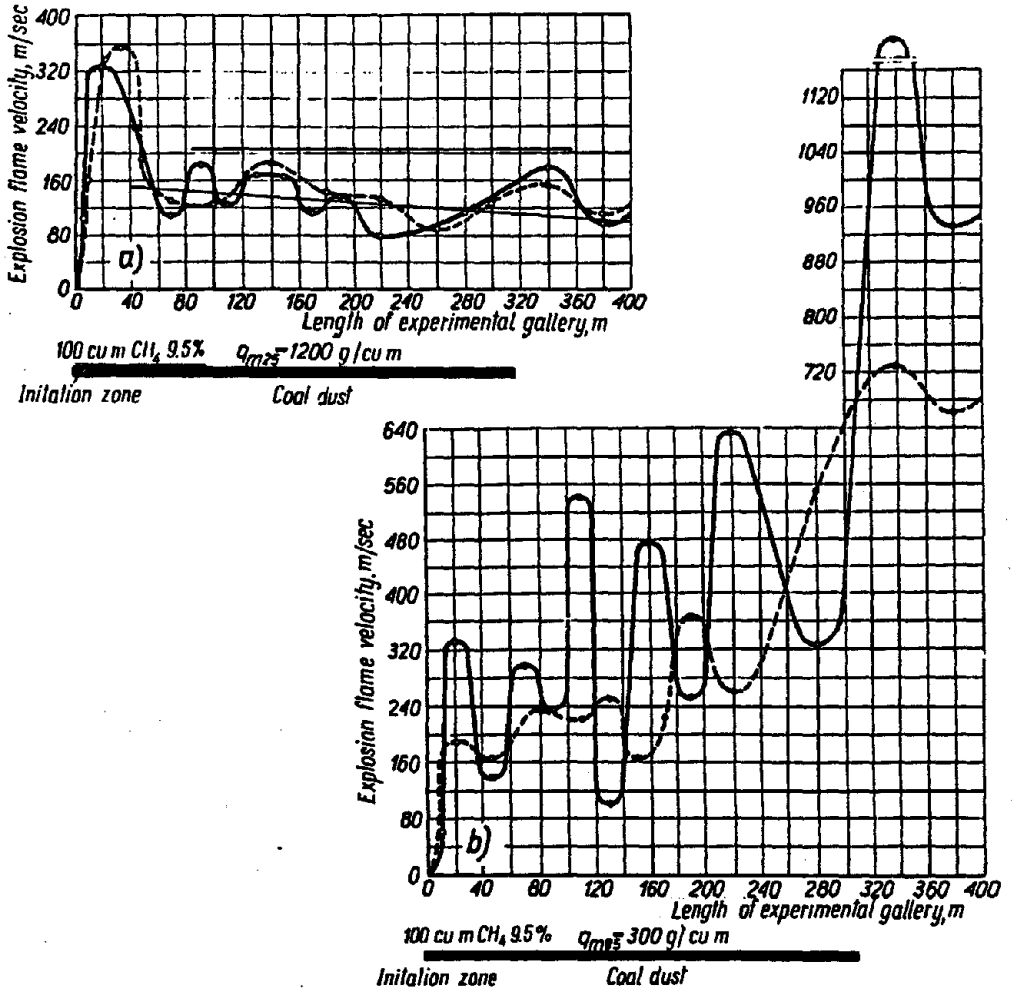


Fig. 4.9. Diagrams of the flame's velocities: *a* — in explosion No. 839 of the d25 *Barbara* coal dust, $n = 60\%$, $q_{m25} = 1200$ g/cu m; ——— measured by detonator method, - - - measured by photoelectric method, $V_{sr\,(60-400)} = 123$ m/sec; $a = 15$ m/sec^2; *b* — in explosion No. 278 of the d85 *Barbara* coal dust, $n = 70\%$, $q_{m85} = 300$ g/cu m; ——— measured by detonator method, - - - measured by photoelectric method.

This fact can be explained very simply. It is known that, in accordance with explanations given in Section 2.3, the separate fractions of the dust participate to a different degree in an explosion. The participation becomes more active as the size of the particles of the dust diminishes.

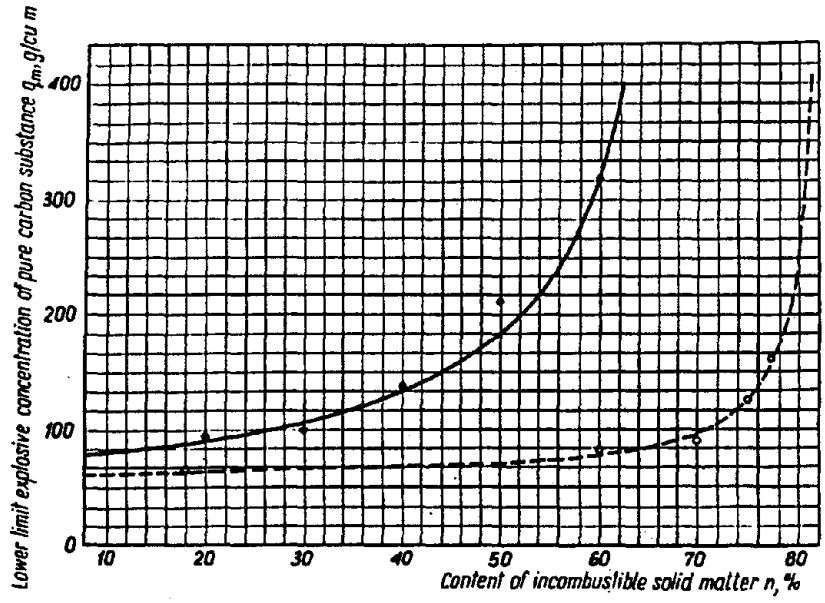


Fig. 4.10. Comparison between the limit explosive concentrations of pure carbon substance for the *d*25 and the *d*85 coal dust at different values of *n* according to equation (4.10) for the *d*25 dust (the curve as shown in Fig. 4.7), and according to equation (4.4) for the *d*85 dust (the curve as shown in Fig. 4.5b); equation (4.10) — curve ——— ●●●; equation (4.4) — curve - - - ooo.

Table 4.8

A Verification of the Consistency of the Function (4.11) with the Results of Experiments

d %	*n* %	*q* g/cu m	Flame range m	Found experimentally q_m, g/cu m	Computed from formula (4.11) q_m, g/cu m
50	50	200	280–300		
50	50	200	300–320	225	198
50	50	225	> 400		
50	60	300	300–320		
50	60	350	> 470	~325	320
15	18.3	126	360–380	~126	126

The difficulties encountered by coal dust in its participation in an explosion grow obviously with the increase in the content in it of limestone dust. This is the reason why, in order to make the development of an explosion altogether possible, it is necessary to have the higher increase of coal dust concentration in the cloud the lower is its fineness.

The above is confirmed by the results of the experiments discussed here.

The big difference between q_{mw25} and q_{mw85} would become considerably smaller if concentrations of pure coal dust < 75 μm is compared with each other

$$q_{mw25} - q_{mw85} = 240.5 \text{ g/cu m} — \text{that is, } 75.7\%$$

On the other hand, the difference between the respective concentrations of the dust of pure carbon substance in fractions < 75 μm amounts to only 12 g/cu m — that is, 15 percent.

4.5. DETERMINATION OF THE LOWER LIMIT EXPLOSIVE CONCENTRATION OF COAL DUST AS A FUNCTION OF ITS FINENESS AND OF THE CONTENT OF INCOMBUSTIBLE SOLID MATTER n

4.5.1. The finding of functions $q_m = f(n, d)$ and $q_{mw} = f(n, d)$

The following functions were determined on the basis of calculations contained in the publication [52]

$$q_m = \frac{549Z - 14d - 54 + \sqrt{\Lambda}}{2(0.048d - Z + 1)} \tag{4.11}$$

where

$$Z = \frac{n}{100 - n}$$

$$\Lambda = (549Z - 14d - 54)^2 + 4(0.048d - Z + 1)(1030d + 74{,}493Z + 9234) \tag{4.12}$$

The formula (4.11) has real solutions for the values of Z satisfying the inequalities

$$0 < Z < 0.048d + 1$$

Analogously to the function $q_m = f(n, d)$, expressed by the equation (4.11), the function $q_{mw} = f(n, d)$ was determined

$$q_{mw} = \frac{82Z - 7.4d + 421 + \sqrt{\Delta}}{2(0.038d - Z + 1.6)} \tag{4.13}$$

where

$$\Delta = (82Z - 7.4d + 421)^2 + 4(0.38d - Z + 1.6)(-557d + 2181Z + 17{,}770) \tag{4.14}$$

The formula (4.13) has real solutions for the values of Z satisfying the inequalities

$$0 < Z < 0.038d + 1.6$$

Other forms of functional relations were also calculated, namely

$$d = f(Z, q_m) \quad \text{and} \quad Z = f(d, q_m)$$

$$d = \frac{(20.96Z - 21.98)q_m^2 + (11{,}515.22Z - 1136.19)q_m + 1{,}561{,}705Z + 193{,}575}{q_m^2 + 292.079q_m - 21{,}603.2} \tag{4.15}$$

$$Z = \frac{(0.0477d + 1.044)q_m^2 + (13.93d + 54.2)q_m - (1030.5d + 9233)}{q_m^2 + 549.27q_m + 74{,}493} \tag{4.16}$$

as well as

$$d = f(Z, q_{mw})$$

and

$$Z = f(d, q_{mw})$$

$$d = \frac{(26.6Z - 43.06)q_{mw}^2 + (2181.75Z + 11{,}200)q_{mw}^2 - (58{,}008Z + 472{,}690)}{q_{mw}^2 + 197.34q_{mw} - 14{,}826.2} \tag{4.17}$$

$$Z = \frac{(0.0376d + 16.2)q_{mw}^2 + (7.42d - 421.02)q_{mw} - 557.38d + 17{,}770}{q_{mw}^2 + 82.02q_{mw} - 2180.7} \tag{4.18}$$

Special tests were carried out to find out whether the formula (4.11) is in conformity with the results of experiments. The results of these tests are presented in Table 4.8. This table confirms that the values of q_m determined experimentally adequately conform with the values of q_m calculated according to the formula (4.11). The results of experiments in which the dusts $d25$ and $d85$ were used are not included in Table 4.8 because their conformity with the formula (4.11) is practically absolute in the entire possible range of the values of n.

4.5.2. Summary of the results of investigations

Using the formula (4.11) it is possible to calculate, with a sufficient accuracy, the lower limit explosive concentration of coal dust containing more than 25 percent of volatile matter.

Such calculations can be made for any degree of fineness of coal dust found in Polish mines of bituminous coal, and for any selected content of incombustible solid matter in coal dust provided that this content does not suffice to make the dust incapable of propagating an explosion.

Formula (4.11), together with formulas which determine the explosibility of coal dust presented in Section 8.10, makes it possible to express in exact terms the hazard of a coal dust explosion in mine workings. It could be assumed that, in determining the degree of the dust hazard, an appropriate security margin is allowed to meet any possible chances.

Of course for calculating the lower limit explosive concentrations all the dust present in the working should be taken into account in spite of the fact that, during an explosion under conditions existing in mines, only part of the dust is raised as a cloud and participates in the explosion reactions. The explanation may be found in the fact that it is exceedingly difficult to collect a quantitative sample of mine dust in workings.

The research work carried out by Stolecki [165] proved that, in spite of a very careful collection of a coal dust sample, the sample in question often indicates the presence of about one half of the quantity of the dust actually present in the working.

It ought to be stressed that the formulas given in Section 4.5.1 refer to the steady propagation of an explosion — that is, to the continuous development of the explosion after the fading away of the direct influence of the initiator. This is quite justified from both the theoretical and practical points of view since in this way the lower limit of explosibility of coal dust is most precisely defined.

Naturally a coal dust explosion developed over long distances causes — as a rule — great disasters. In practice, however, a relatively short range of the explosion flame, for example, on extending over 100 m, might cause a serious disaster depending on local conditions.

4.5.3. Nomograms for finding the value of q_m according to the formula (4.11)

Actually a lot of work must be done in order to calculate the values of q_m according to the formula (4.11) especially on account of the fact that in this formula the magnitude d refers to the fineness of coal dust without stone dust, so that the use of this formula (4.11) depends upon the finding of the value of d. Employing the direct sieve method the value of d_m is found in a collected sample of coal dust — that is, the percentage of the fraction of the mixture of coal dust and stone dust passing through a sieve of 75 μm mesh.

In order to determine the value of d the following formula should be used

$$d = \frac{100 d_m - 0.6n}{100 - n} \tag{4.19}$$

Nomograms were worked out and presented in Figs. 4.11 and 4.12 which facilitate the determination of the value of q_m on the basis of the values of d_m and n determined directly by the chemical and physical analysis. The nomogram given in Fig. 4.11 is well suited to cases where

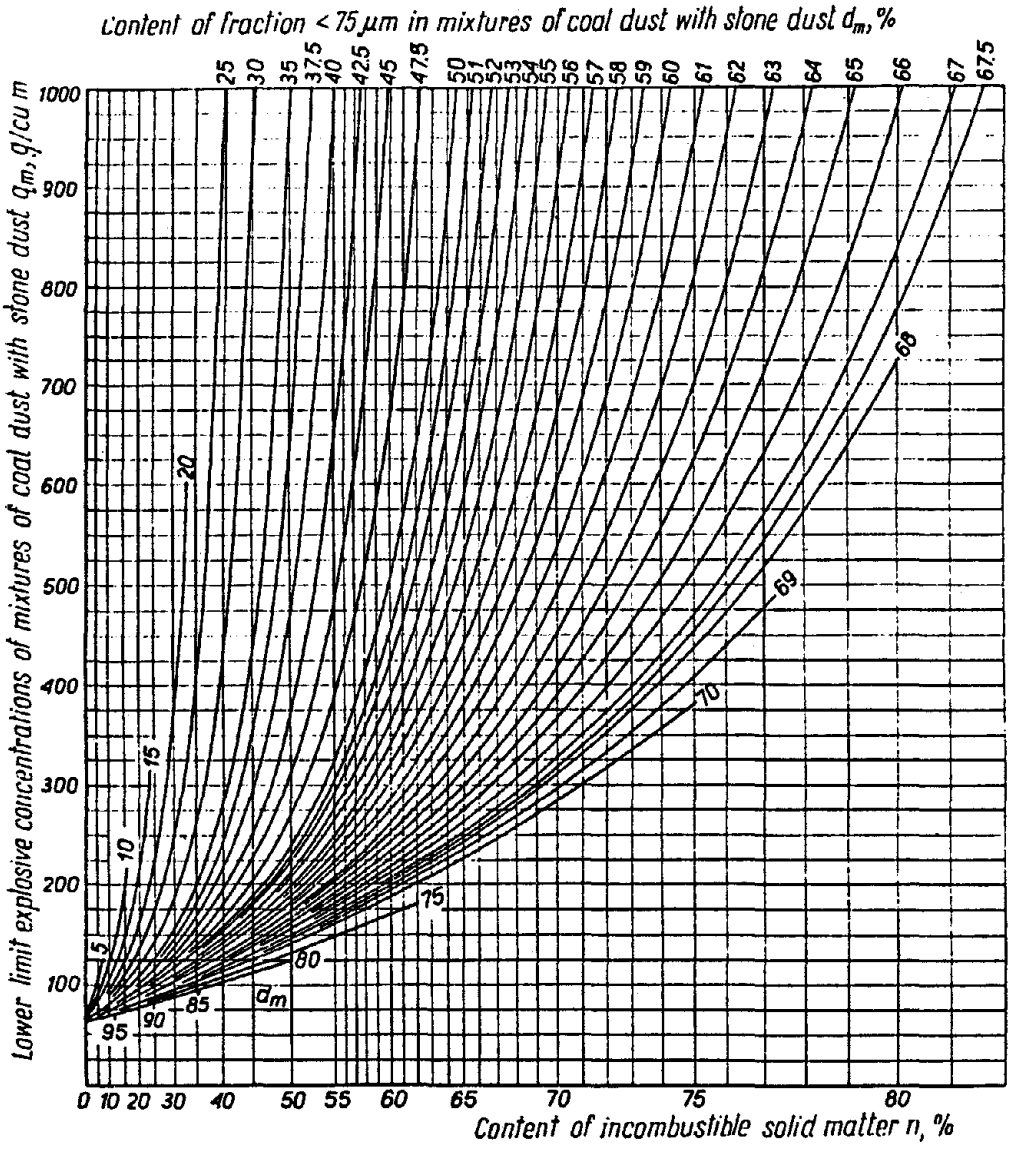


Fig. 4.11. Nomogram for finding the value of q_m as depending upon n and d_m according to equation (4.19); the use of this nomogram is indicated for the values of n from 55 to 80%.

the values of n are comprised between 55 and 80 percent, while the nomogram in Fig. 4.12 to cases in which this value is between 0 and 55 percent.

The use of nomograms is very simple.

For different values of d_m curves are plotted representing the dependence of q_m upon n.

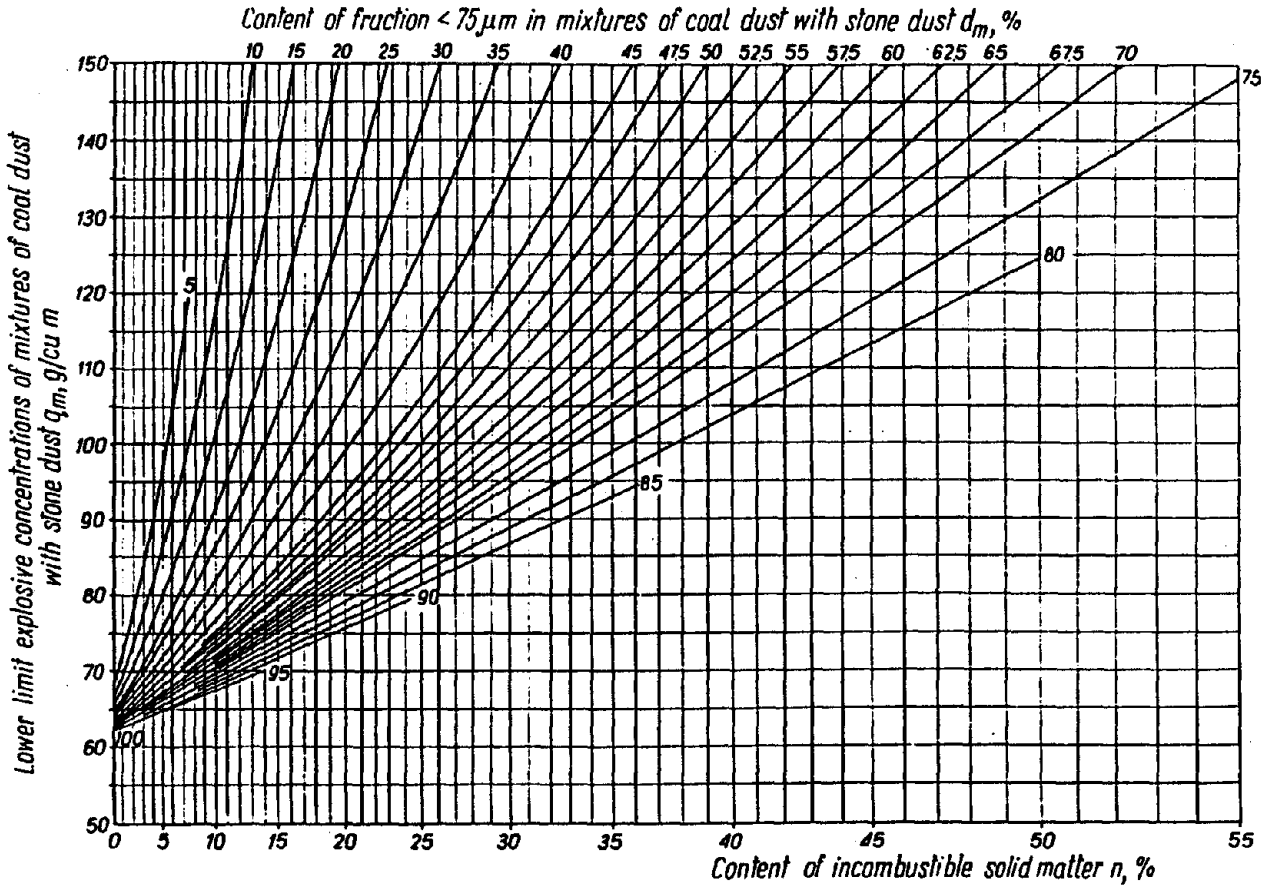


Fig. 4.12. Nomogram for finding the value of q_m as depending upon n and d_m according to equation (4.19); the use of this nomogram is indicated for the values of n from 0 to 55%.

Drawing a perpendicular from the point representing the determined value of n and extending it to the curve representing the determined value of d_m we find the point on the curve through which a line should be drawn parallel to the x-axis. This line, when extended to the y-axis, will indicate the looked-for value of q_m.

Of course, interpolation should be used in cases when the determined value of d_m is placed between the relevant curves.

The purpose of the elaboration of two nomograms had been to ensure more accuracy in determining the values of q_m. The details of the elaboration of nomograms are given in the work [70].

4.6. THE UPPER LIMIT EXPLOSIVE CONCENTRATION Q_m OF COAL DUST

4.6.1. Investigations on the Q_m for pure coal dust

Foreign research institutions have not determined the Q_m. Taffanel was convinced that it is impossible to determine the upper limit of explosibility of coal dust saying (verbatim): "There is no upper limit of explosibility of coal dust; for even with the highest quantities of dust per cu m an explosion and its propagation had taken place."

British research workers Wheeler and Mason likewise did not determine the Q_m because of the difficulties they had in forming a cloud of dust of the desired concentration extending over a sufficiently long zone of the experimental gallery [118].

In the *EM Barbara* the values of Q_0 and Q_m were determined under the dust dispersion conditions described in Section 4.2.1. These conditions permitted of raising into the air the entire coal dust and of dispersing it with adequate eveness in the cross section of the gallery. The tests were carried out only in the 100 m surface experimental gallery where it had been easier to attain an even dispersion of the dust in its cross section than it would have been in an underground experimental gallery.

The results of the determination of Q_0 and Q_m were rather unexpected. As can be seen from Table 4.2 the values of Q_m for the five types of examined coal dusts had shown the difference of only 0.1 kg/cu m, in four cases amounting to 0.9 kg/cu m and only in one case to 0.8 kg/cu m. It may be assumed, therefore, that the value of Q_m is a constant magnitude for all types of bituminous coal dust and that it remains constant within a very wide range of the content of volatile matter in the coal dust, from $V = 18.3$ percent to $V = 31.5$ percent.

In other words for four of the examined kinds of dust $Q_m = 0.9$ kg/

/cu m, and $Q_0 = 1.00$ kg/cu m; only for one kind of dust these values were lower by 0.1 kg/cu m.

Thus it was experimentally established that all examined dusts had approximately the same upper limit of explosibility in spite of widely varying V and d values.

4.6.2. The effect of incombustible solid matter n in coal dust on the upper limit of explosibility Q_m

It has been found — in an underground experimental gallery — that the upper limit of explosibility Q_m of the mixture of coal dust with limestone dust, containing 60 percent of incombustible matter, amounts to about 1000 g/cu m — that is, only by 100 g more than the corresponding value found in a surface experimental gallery for pure coal dust. The value of Q_m found in the surface experimental gallery for an identical mixture was 900 g/cu m.

The established fact of practically equal values of Q_m for various kinds of coal dusts and for their mixtures with stone dust is explained by the circumstance that the propagation of a coal dust explosion occurs because heat energy is being transmitted through radiation. At very high concentrations of coal dust a state is reached when particles of coal dust and particles of stone dust begin to act jointly as screens of a surface that prevents the transmission of the heat energy through radiation. Another explanation of the phenomenon of the practical stability of the value of Q_m may also be given by referring to the ordinary absorption of heat by the highly concentrated dust as a result of which the temperature of coal dust particles is being brought below the temperature necessary for the development of an explosion.

It would not be out of place to mention here that, in the discussed phenomenon, undoubtedly a certain role is played by the sorption of oxygen by hot particles of coal dust and also by the fact that the upper limit of explosibility of mixtures of inflammable gases (evolved through the pyrolysis of carbon) with the air is transgressed.

5. THE EFFECT OF THE INITIATOR OF THE EXPLOSION ON THE EXPLOSIBILITY OF COAL DUST

5.1. FACTORS MOST COMMONLY INITIATING EXPLOSIONS OF COAL DUST

In the action of an explosion initiator two factors are of paramount importance: the factor which causes the raising of a cloud of coal dust, and the factor igniting this cloud. Upon the magnitude of these factors, and their synchronization, depends the ability of a given initiator to start an explosion. The two factors may come from the same source or from different sources. The most dangerous are the sources which can simultaneously both raise and ignite a cloud of coal dust.

In mines the factor which most frequently raises clouds of dust is a blast of air — a blast of gases to use a more general term. The factor igniting a dangerous cloud of coal dust may be called generally the thermic factor. According to information given in Section 2.2 the minimum quantity of energy sufficient to ignite coal dust — as determined through tests carried out in Poland — amounts to 200 mJ; according to American investigations it is even lower. The lowest ignition temperature of the Polish bituminous coal dust amounts to 783°K (510°C).

When the factor raising a cloud and the thermic factor igniting this cloud come from two independent sources the necessary condition of the initiation of an explosion is their synchronization.

As far as the initiation of an explosion in a mine is concerned the most dangerous are explosions of methane or of flammable fire gases and shotfiring since they automatically synchronize both the appearance of the blast and the thermic factor at the moment when the dangerous cloud of coal dust is already formed.

So long as open light was allowed in nonmethane seams the thermic factor capable of igniting a cloud of coal dust has been present wherever the flame of acetylene lamps appeared. When open light became excluded from mines this factor ceased to exist. However, apart from gas explosions and shotfiring, there still exist other possibilities of an ignition of a coal dust cloud. In the first line mention should be made here of the shorting

arc and the grounding arc which ignite very easily a cloud of coal dust. Also a match used to light a cigarette may cause the ignition of a dust cloud.

Among the possible causes of the initiation of a coal dust explosion, methane explosions should be named in the first place. While explosions of flammable fire gases are also very dangerous, yet their occurrence is not so frequent. As a result of shotfiring dangerous clouds of coal dust are very easily formed but the ignition of coal dust through explosives, allowed in the winning of coal, is very difficult.

5.2. THE MINIMUM QUANTITY OF THE EXPLOSIVE MIXTURE OF FIREDAMP SUFFICIENT TO INITIATE A COAL DUST EXPLOSION

5.2.1. General information

The knowledge of the process of initiation of a coal dust explosion by firedamp is of great practical importance. Thus, undoubtedly, the determination of the minimum quantity of firedamp sufficient to initiate a coal dust explosion constitutes a fundamental problem.

American research workers [140] found that the minimum quantity of methane, sufficient to initiate an explosion of coal dust capable of a development, amounts to 4.135 cu m. It should be noted that the problem discussed touches upon the quantities of methane not only capable of igniting a dust cloud but capable also of initiating an explosion of coal dust — that is, of raising a primary cloud of the kind which, being ignited, may become the cause of the propagation of the explosion of coal dust. Methane can accumulate in the entire cross section of workings, in the spaces behind the support, in cavities at the face, in cuts, and under the roof. It can also accumulate in abandoned workings and is present, as a rule, in the methane offtake pipelines.

Among the above enumerated accumulations of methane, capable of initiating a coal dust explosion, the most common are accumulations in the voids behind the support and in the cavities at the very face of workings. The accumulation of methane in the entire cross section of workings require the largest quantities of methane to be able to initiate a coal dust explosion.

It should be added that the overall dimensions of methane accumulations in mines vary quite considerably. Therefore in the discussion of this subject it was necessary to adopt certain simplifications.

5.2.2. The minimum quantities of firedamp — concentrated in small spaces — capable of initiating a coal dust explosion

The effects of an explosion of firedamp may vary considerably depending upon the concentration of CH_4, its quantity and the place in which it had accumulated.

In order to initiate a coal dust explosion through the accumulation of methane in the entire cross section of a working, larger quantities of methane are required than in the case of methane accumulations in cavities of smaller cross sections.

An accumulation of methane in an underground gallery of a cross section equal to approximately 3 sq m must extend over a part of this gallery at least 1 m long to produce, when methane is ignited, a blast sufficiently strong to raise a dangerous cloud of coal dust.

The tests described in the present section were carried out for the purpose of determining the minimum quantities of methane capable of initiating an explosion of coal dust; therefore, the conditions under which these tests were performed resembled the most disadvantageous conditions that can occur in practice.

The basic data, concerning the effects of a firedamp explosion, establishes the fact that the effect of the explosion of a given quantity of firedamp varies depending on the cross section of the gallery and on the location of the ignition of firedamp. As was mentioned previously methane accumulates relatively easily in the cavities in the roof and in those at the face of a working. These cavities can have different shapes. Depending on their overall dimensions the same quantity of firedamp, of the same degree of concentration, can produce different explosion effects. Of the fundamental importance here is the energy of the blast produced by the explosion. Namely, this blast must be sufficiently strong to raise a primary cloud of coal dust of an explosive concentration and of a sufficient volume. The development of the flame in this cloud must, in its turn, produce a sufficiently strong blast to raise a secondary cloud capable already of propagating the explosion. As it is impossible to reproduce the various accumulations of firedamp one meets in practice, it was necessary to carry out the tests under certain fixed conditions considered to be very favorable to the initiation of a coal dust explosion.

In order to ensure such conditions for the tests in question methane was placed in pipes 800, 700 and 500 mm in diameter. Details of the results of the tests are contained in the publication [64]. In Fig. 5.1, as an example, a pipe 500 mm in diameter is shown, located in an experimental gallery, and the way in which coal dust had been distributed so that its raising and dispersion in the form of a dangerous cloud should be made easy.

Pipes 800 and 700 mm in diameter were located in an experimental gallery in the same manner as that shown in Fig. 5.1.

Sections of the pipe were divided from each by paper partition so that appropriate firedamp chambers were formed. The pipes had the bottom inside of which firedamp had been ignited by an electric detonator.

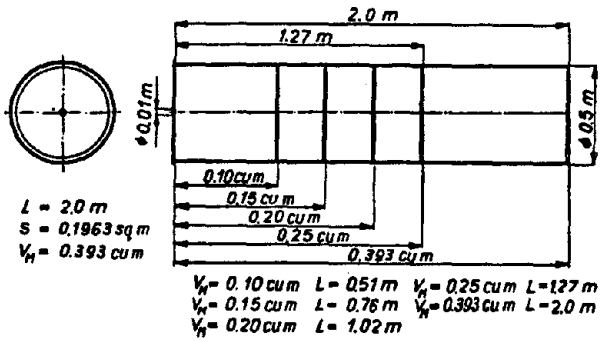


Fig. 5.1. A diagram showing the pipe 500 mm in diameter for investigating the $V_{M\,min}$ initiating coal dust explosions in the 44 m surface experimental gallery.

To ignite very dangerous coal dust very small quantity of energy (200 mJ) will suffice. Since for the initiation of a coal dust explosion it is essential that the magnitude of the pressure of the blast should suffice to raise a dangerous primary cloud of coal dust, the dynamic pressure was measured in all of the tests performed at the outlet of the pipe and at a distance of 1 m from the outlet.

On the basis of oscillograms thus obtained the dynamic pressure rate $\frac{\Delta P}{\Delta t}$ kN/sq m·sec was determined.

By changing the volume of methane either the ignition of the raised cloud of coal dust was effected or the propagation of an explosion throughout the entire gallery is obtained. Only the last mentioned results were considered as conclusive for the determination of the minimum volume of methane $V_{M\,min}$ necessary to initiate an explosion of coal dust.

The d85 and d25 *Barbara* coal dusts were used in these tests.

Altogether 195 explosions of methane and of coal dust were made. The scatter of the results, consisting in either the propagation of explosions or the ignition of coal dust, is — unfortunately — irregular which fact made a statistical analysis impossible. Table 5.1 contains a summing up of the results of tests on the initiation by methane of coal dust explosions in pipes 800 and 500 mm in diameter. As is shown in this table the minimum volume of an explosive mixture of methane $V_{M\,min}$, sufficient to initiate an explosion of coal dust, is very small amounting to $V_{M\,min}$ =

$= 0.15$ cu m for the d85 coal dust, and to $V_{M\,min} = 0.20$ cu m for the d25 coal dust. With an increase in the diameter of the pipe used in the test the value of $V_{M\,min}$ also increases.

The value of $V_{M\,min} = 0.15$ cu m as given above, determined in a pipe 500 mm in diameter, cannot be regarded as actually the minimum value. Tests in which pipes of a smaller diameter would have been used might have led to the determination of still lower values of $V_{M\,min}$. However, there was no practical necessity of extending investigations in this direction. It ought to be stressed that the established value of $V_{M\,min} = 0.15$ cu m refers to the mixture of methane with air approaching the stoichiometric one so that an emission of only about 0.015 cu m of CH_4 will suffice to initiate a coal dust explosion. This small amount of methane is an eloquent illustration of the hazard connected with methane as a possible initiator of coal dust explosions. Table 5.1 contains also the values of $\frac{\Delta \bar{P}_1}{\Delta t}$ for the limit magnitudes $V_{M\,min}$. These values for the same types of dusts are very close to each other.

Table 5.1

A Summary of the Results of Investigations on the $V_{M\,min}$ of Methane for Igniting Coal Dust in Pipes

Pipe diameter mm	Coal dust	$V_{M\,min}$ cu m	$\frac{\Delta \bar{P}_1}{\Delta t}$ g/sq m millisec	Dynamic pressure $\bar{P}_1$ kN/sq m
800	*d*85	0.3	2.0	3.5
	*d*25	0.5	7.3	7.9
500	*d*85	0.15	2.7	5.7
	*d*25	0.20	7.8	8.0

5.2.3. Dynamic pressures sufficient to raise dangerous coal dust clouds

Pressures sufficient to initiate coal dust explosions depend upon the entirety of local conditions characterizing the pertinent enclosed space, as well as upon the kind and distribution of coal dust. The values of pressures given in Table 5.1 refer, naturally, to the totality of conditions under which tests were carried out.

In Table 5.1 attention is drawn to dynamic pressures $\bar{P}_1$ determined for $V_{M\,min}$. For the *d*25 dust the values of $\bar{P}_1$ are almost identical in the cases of pipes of both diameters and amount to about 8.0 kN/sq m. For the *d*85 dust the values of $\bar{P}_1$ are still lower. In the pipe 800 mm in di-

ameter P_1 equals ~3.6 and 7.9 kN/sq m. These figures show how low dynamic pressures might suffice to raise a dangerous cloud of coal dust. The dependence of the values determined for mean dynamic pressure upon the volumes of methane chambers is described by the following regression equation

$$P_1 = 26.4 + 149.5\,V_M + 542.8\,V_M^2 \qquad (5.1)$$

Equation (5.1) refers to the relation between P_1 and $V_{M\,min}$ for the $d85$ dust under conditions fixed by the use of a pipe 500 mm in diameter. The value of P_1 in equation (5.1) is expressed in kN/sq m.

The correlation index $R = 0.7764$; the mean error of the regression $S_{P_1V} = 42.1$; the standard deviation $V = 65.7$.

Equation (5.1) is presented in a graphic form in Fig. 5.2.

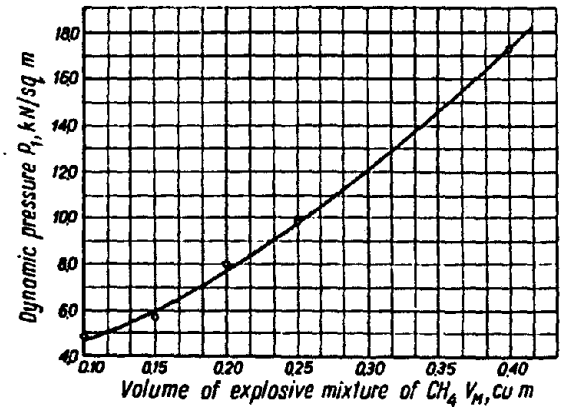


Fig. 5.2. A diagram expressing the dependence of the mean dynamic pressures P_1 upon the volume $V_{M\,min}$ in a 500 mm pipe according to regression equation (5.1).

Table 5.1 does not contain the results of measurements of dynamic pressures at a distance of 1 m from the outlet of the pipes. The values so determined were considerably lower than those recorded at the outlet of the pipes averaging for methane chambers of the volume of:

0.4 cu m	4.4 kN/sq m,
0.15 cu m	2.4 kN/sq m,
0.10 cu m	2.3 kN/sq m.

5.2.4. The minimum quantities of firedamp which may cause the initiation of a coal dust explosion by shotfiring

Shotfiring causes the raising of coal dust clouds much the same as an explosion of firedamp does. This phenomenon occurs always at working

faces where dry coal dust is present, which means daily and on a vast scale.

When rock explosives are used and shotfiring is not done according to rules the ignition of coal dust becomes very easy since the appearance of the dangerous flame produced the detonation, or the explosion of the explosive is synchronized with the formation (the raising) of a dangerous coal dust cloud. Thus at the time when blasting powder had been used on a large scale, and when coal mining and permitted safety explosives were not yet known, shotfiring was the cause of many a disastrous explosion of coal dust. Permitted safety explosives now used in coal mines are safe to a high degree in the presence of coal dust. Coal mining explosives, however, are not safe in the presence of methane and, if used in a seam containing methane, can cause its ignition; obviously if rock explosives are used the ignition becomes much easier.

It is easy to conceive that the flame of a detonation of an explosive cannot by itself ignite coal dust. However, if a detonation of an explosive should happen to ignite even a small quantity of methane the effect produced would be such that the hot detonation products, together with the ignited methane, can initiate the ignition of a coal dust cloud. In other words: while the products of a detonation by themselves cannot ignite coal dust yet, with some addition of methane, might become capable of doing so. This phenomenon ought to be discerned from the simple ignition of methane by firing an explosive. The quantities of methane which create the hazard in question can be very small.

On account of considerable difficulties involved, scientific literature does not contain any research reports on exactly this subject. That is, the minimum quantities of methane are not determined which, for example, when coal mining or permitted explosives are used may — under particularly dangerous conditions — cause, jointly with detonation products, the ignition of coal dust initiating an explosion. On the other hand, tests were carried out [64] to determine the minimum quantity of methane sufficient to initiate a coal dust explosion when a charge of 50 g of black powder is fired, the firing of the same charge by itself having failed previously to ignite coal dust. As a result of these tests it was established that, under such conditions, the minimum volume of methane sufficient to ignite the $d85$ coal dust amounted to 0.1 cu m and in the case of the $d25$ coal dust slightly exceeded 0.4 cu m. In analogous tests, when the charge fired consisted of 100 g of rock Ammonite 5 which by itself, under the same test conditions, failed to ignite coal dust the minimum volume of methane which, jointly with detonation products of the explosive, caused the ignition of the $d85$ coal dust amounted to 0.25 cu m. The above

very slight volumes of methane illustrate its influence on the safety of an explosive in the presence of coal dust.

Methane content in the air beneath the lower explosibility limit facilitates the ignition of coal dust by an explosive. Thus the presence of 2 to 3 percent of CH_4 in the mine air might, under favorable conditions, cause the ignition of coal dust not only by a coal mining explosive but even by a permitted explosive.

5.3. ACCUMULATIONS OF FIREDAMP BEHIND THE SUPPORT

Accumulations of CH_4 in explosive concentrations occur most frequently behind the support in workings and galleries. The regulations in force at the time of the writing of this book do not demand that methane concentrations behind the support should be controlled. Therefore, uncontrolled accumulations of methane behind the support occur and threaten either to become a direct cause of coal dust explosions or to play a prominent part in such explosions. Accumulations of methane behind the support are particularly dangerous when they are present in the vicinity of the faces at which shotfiring operations are conducted. During the shooting behind the blast wave, caused by the detonation of an explosive, runs a wave of rarefaction which causes the sucking out (the drawing out) of methane from behind the support of the working. In this way in a working in which, before the shooting, there was no accumulation of methane exceeding permissible concentrations (1 percent of CH_4 at the distance of 10 cm from the support or from the open roof), an explosive mixture appears suddenly. In the case of delay shotfiring, which is the method most frequently employed, the last of the consecutive shots are fired in the presence of an explosive mixture of methane in the working. Even in the case of instantaneous firing there is the danger of methane being ignited if the explosive deflagrates in one of the shotholes. Not only shotfiring operations but also other factors may cause the ignition of methane. Therefore, the presence of uncontrolled accumulations of methane greatly increases the danger of the initiation of a coal dust explosion particularly when the fact is taken into account that, under unfavorable conditions, very small volumes of an explosive mixture of methane suffice to initiate an explosion of coal dust.

Accumulations of methane behind the support are very easily formed when methane is effused from the roof — that is, from the foigs. Most frequently methane accumulates behind the support when a seam of coal containing methane is situated there. This occurs often in the cases in which workings are driven in thick seams in such a way that coal remains

in the roof of the workings. The same happens when, above the roof of a working, thin methane-containing seams of coal are situated, the so-called accompanying seams which are not exploited; the whole formation being disturbed, such seams crack and frequently effuse very high amounts of methane.

When methane is not effused from the roof there is practically no accumulation of CH_4 behind the support resulting from its evolution from the air flowing through a given working. Methane mixed with the air practically does not separate itself from the latter in spite of its much lower specific gravity. Methane from the working itself can accumulate behind the support only if there is a strong floor or sidewall squealer in the working so that the air flowing through the working does not mix with CH_4. This may happen when the effusion of CH_4 from the floor or the sidewalls of a working is very strong especially if the air flows through the working at low velocities.

If it is not possible to remove immediately dangerous accumulations of methane from behind the support neither with the aid of nozzles, connected to compressed air pipelines, nor barriers which would have increased the velocity of the air under the roof, nor with the aid of perforated ventilation pipes, then the places in which dangerous accumulations of methane were discovered ought to be marked on the plans of the mine to make certain that the existence of these accumulations will not be forgotten.

If a dangerous accumulation of methane behind the support is situated at a distance of less than 50 m from the face of the working at which shortfiring operations are conducted, these operations ought to be carried out with such precautionary measures enhancing their safety as are indicated by regulations and instructions.

It should be remembered that accumulations of methane of very diverse concentrations always appear in seams containing methane in the cuts.

The accumulations of methane behind the support are encountered less frequently where there is main ventilation than when it is of the auxiliary type.

Two kinds of methane accumulations behind support ought to be discerned: a dangerous and a directly dangerous kind.

To the dangerous kind, accumulations of methane of concentrations from 2 to 5 percent are counted. When such concentrations of methane are discovered extending over a length of not less than 10 m periodical controls must be made to make certain that the concentration of methane did not rise above 5 percent.

An accumulation of methane behind the support is considered to be

directly dangerous if the concentration of CH_4 equals or exceeds 5 percent and more, and:

— its presence is discovered behind the support of a working and it extends over a length equal to 10 m or more if such a concentration of CH_4 is discovered above the support at a depth of less than 1 m measured from the lining of the support,

— irrespective of the length over which it extends when the above concentration of CH_4 is discovered in the space above the support at a depth of 1 m measured from the lining of the support.

Accumulations of methane (which constitute a direct danger) behind the support of a concentration equal to, or exceeding, 5 percent ought not to be confused with firedamp fuses.

Directly dangerous accumulations of methane behind the support can, the same as firedamp fuses, transmit the flame of burning methane but they create also a serious hazard of an explosion which, in its turn, can initiate an explosion of coal dust.

Firedamp fuses will be discussed in a separate chapter.

Directly dangerous accumulations of methane behind the support occur in coal and, less frequently, in stone workings. The hazards connected with accumulations of methane behind the supports of these workings differ from each other and require different rigors [46].

5.3.1. Roof layers of firedamp capable of initiating a coal dust explosion

5.3.1.1. Roof layers of firedamp and their basic definitions. In mine workings, whenever methane is effused from the roofs, the so-called roof layers of firedamp are formed. They are very dangerous because CH_4 in this form in explosive or higher concentrations enters the free cross section of working behind the support. Roof layers of firedamp is the name given to thin layers of a mixture of methane with the air of a concentration exceeding 5 percent. These layers can spread out over long sections of mine workings.

On account of the fact that the notion itself of methane accumulations within the free cross section of a working is apt to raise doubts and creates misunderstandings a classification of these accumulations and their definitions are given below. First of all it is necessary to describe the method of measuring methane accumulations as determined by the binding regulations for the purpose of evaluating: the permissibility of admitting workers, the possibility of conducting shotfiring operations and the possibility of using electric equipment.

For these purposes the concentration of methane ought to be measured — according to binding regulations — at a distance not exceeding

10 cm from the open roof, or at a distance not exceeding 10 cm from the lining when the working is lined. In order to determine the concentration of methane, samples of the air are collected and analyzed. The result of the analysis shows the concentration of methane. Methane detectors can also be used.

Measurements taken with the aid of the safety lamp are not conclusive, indeed, since with this lamp it is not possible to measure the concentration of methane at a strictly fixed distance, for example, 10 cm from the roof or from the lining. In Great Britain special safety lamps are used for the purpose discussed here but this is done, it seems, for reasons of economy. If the concentration of methane, measured correctly, amounts to 1 to 2 percent then — according to regulations — we are dealing with an accumulation of methane. In a case like this shotfiring operations are permitted with restrictions as to the explosive which can be used, or as to the method of winning coal (e.g., the Armstrong method).

If the measurements show the concentration to equal or exceed 2 percent of CH_4 miners are not admitted to the working in question.

When the concentration of methane amounts to less than 2 percent an examination of the place (the working) ought to be made to establish the possible presence there of dangerous roof layers of methane. Measurements are taken directly under the open roof or under the lining. If the measurement shows 5 percent or more of CH_4 we stand in the presence of a dangerous roof layer of methane. This layer might actually be either a firedamp fuse or a directly dangerous layer of methane.

The firedamp fuse is a roof layer of methane, not less than 10 m long, which — when ignited — can transmit the flame but cannot cause an explosion of coal dust.

A roof layer of methane is considered to be directly dangerous when it is capable, when ignited, not only to transmit the flame but also to initiate a coal dust explosion.

5.3.1.2. Results of investigations carried out in the underground experimental gallery on the interdependence between the thickness of the roof layers of firedamp sufficient to initiate an explosion of the *d*85 coal dust and the length of these layers. It stands to reason that the minimum thickness of a directly dangerous roof layer of firedamp, sufficient to initiate an explosion of coal dust, depends upon the length of the layer.

The examination of this dependence is a matter of considerable practical importance since, on the basis of the results of the pertinent investigations, it is possible to define with more accuracy the firedamp fuse — that is, to determine the thickness of a roof layer of firedamp at which it is capable of transmitting the flame, yet cannot initiate an explosion of coal dust.

Though the matter is quite important nobody outside of Poland has carried out, or published, the results of such investigations.

The investigations, the results of which are presented below, were carried out in the *EM Barbara*. They furnished the possibility of determining the minimum quantity of methane in the form of a roof layer sufficient to initiate an explosion of coal dust under given conditions.

Tests were carried out in the 400 m underground experimental gallery the roof of which represents a circular arc, the radius of the circle being equal to 275 cm. Figure 5.3 shows a cross section of this gallery

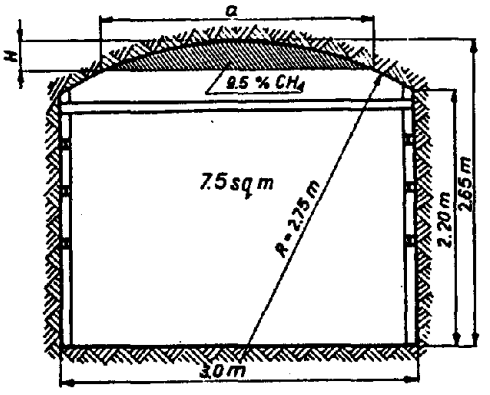


Fig. 5.3. Cross section of the experimental gallery containing a roof layer of methane.

together with the roof layer of methane. In order to form a roof layer of methane the roof space of the gallery had been cut off by a paper diaphragm. This procedure was necessary in order to determine precisely the parameters of the layer and to create repeatable test conditions. The parameters are expressed as follows:

H — the thickness of the methane layer at the highest point, cm,

L — the length of the methane layer, m,

S — the lateral cross section of the methane layer, sq m,

V — the volume of the methane layer, cu m.

In the course of the tests in which coal dusts $d85$ and $d25$ were used the above parameters were being changed within the following limits:

H — from 10.5 to 5.2 cm,

L — from 40 to 2.5 m,

S — from 2.8 to 0.037 sq m,

V — from 13.5 to 1 cu m.

Methane was ignited by an electric detonator placed at the very face of the gallery in the roof layer of methane. By way of an example in Fig. 5.4 two graphs are shown illustrating the velocities of the flame for

two different concentrations of methane in methane layers, the parameters of which are given in the figure.

Dry coal dust was placed on roof bars and on boards under conditions facilitating its dispersion by the blast caused through the combustion of methane. The dust was distributed in the gallery over a length sufficient for ascertaining whether the ignition of coal dust does, or does not, develop into an explosion capable of propagating itself independently.

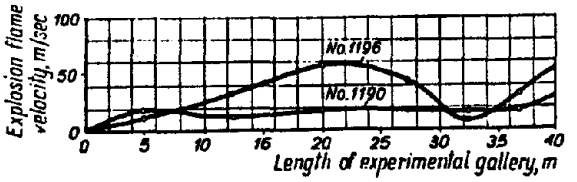


Fig. 5.4. Diagrams of methane flame velocities in roof layers given by way of examples: explosion No. 1190: $H = 5.2$ cm, $L = 40$ m, CH_4 concentration = 7.5%, $V_M = 1.5$ cu m; explosion No. 1196: $H = 5.2$ cm, $L = 40$ m, CH_4 concentration = 9.6%, $V_M = 1.5$ cu m.

On the basis of the results of these tests the following regression equations were determined for the $d85$ coal dust expressing the interdependences between H and L (5.2), S and L (5.3) and V and L (5.4)

$$H = \frac{143.6}{L - 1.06} + 2.1 \tag{5.2}$$

$$S = \frac{2.3505}{L - 1.6093} - 0.022 \tag{5.3}$$

$$V = \frac{0.2163 + 2.2602L - 0.0183L^2}{L - 1.6093} \tag{5.4}$$

In Fig. 5.5 a graphic expression is presented of the regression equation (5.2) — that is, the hyperbola expressing the relation between the minimum thickness of roof layers of methane H and the lengths of roof layers of methane L for the $d85$ coal dust. Graphic expressions of regression equations (5.3) and (5.4) are given in the publication [61].

The lowest value of H determined experimentally, with $L = 40$ m, for the $d85$ coal dust amounted to 5.2 cm.

In a case in which the cross section of a roof layer of methane is rectangular the calculated thickness of the layer for the same coal dust would amount to 3.5 cm.

By applying extrapolation to equation (5.2) it is found that, in the case of the $d85$ coal dust, H tends asymptotically toward the value of 2.1 cm. In a case of the rectangular shape of the roof layer of methane this value would amount to 1.4 cm.

On the basis of the above investigations, taken as a whole, it can be concluded that a roof layer of methane of a thickness below 1.4 cm, irrespective of the length of the layer, is not capable of initiating an explosion even of a very dangerous coal dust.

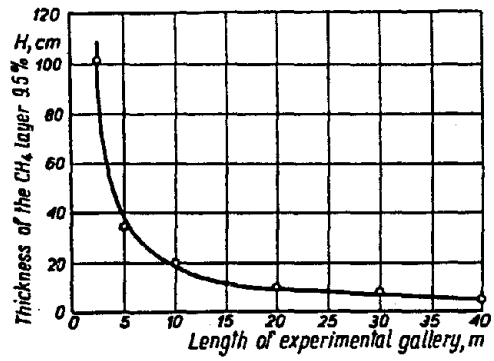


Fig. 5.5. A graphic presentation of regression equation (5.2) expressing the dependence of the minimum values of the thickness of the roof layer of methane *H*, capable of initiating an explosion of the *d*85 coal dust, upon the length of the roof layer of methane *L*.

Accordingly as firedamp fuses can be classified such roof layers of methane whose concentration is above 5 percent but the thickness is below 1.4 cm. For practical purposes this last value may be reduced to 1 cm. This value furnishes a wide margin of safety considering that the *d*85 coal dust had been used and the most favorable conditions of its dispersion were provided in the tests.

At the initiation of a coal dust explosion, in the stage of the formation of the explosive medium through the raising of coal dust, an enormously important role is played by the phenomenon of turbulence. Research work in this direction is most decidedly indicated.

The paper diaphragm, separating the explosive roof layer of methane mixture in the tests carried out in the *EM Barbara*, obviously did facilitate the proceedings, yet the conditions thus created were markedly different from those which exist in mines. Therefore, the difficulties of carrying out such experiments notwithstanding, the tests concerning the initiation of coal dust explosions by roof layers of methane — at different concentrations of this gas — ought to be made without diaphragms separating methane layers.

5.3.1.3. Results of investigations carried out in the underground experimental gallery on the interdependence between the thickness of the roof layers of firedamp sufficient to initiate an explosion of *d*25 coal dust and the length of these layers. Tests analogous to those carried out with the *d*85 *Barbara* coal dust were also made with *d*25 coal dust.

On the basis of the results of these tests the following regression equations were determined for the d25 coal dust expressing the interdependences between H and L and S and L

$$H = \frac{212.9}{L-0.49} + 2.4 \tag{5.5}$$

$$S = \frac{4.3153}{L-0.9850} - 0.053 \tag{5.6}$$

The regression equation (5.5) is presented in a graphic form in Fig. 5.6a, and the regression equation (5.6) in Fig. 5.6b.

The lowest value of H found experimentally, with $L = 40$ m, for the d25 coal dust amounted to 7 cm. In the case of a rectangular cross section of a roof layer of methane its calculated thickness for the same coal dust would amount to 5 cm.

Extrapolating the equation (5.5) it is found that the value of H for the d25 coal dust tends asymptotically toward 2.4 cm. In the case of a rectangular roof layer of methane the last-mentioned value would amount to 1.6 cm.

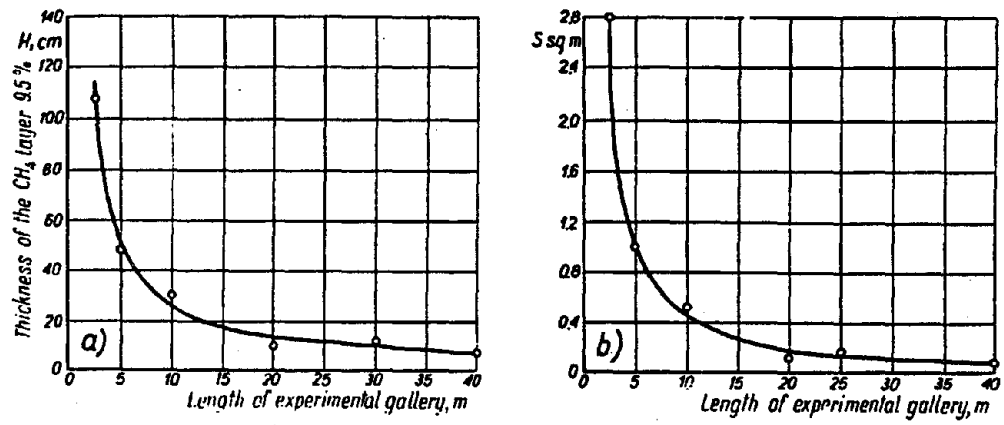


Fig. 5.6. Graphic presentations: a — of regression equation (5.5) expressing the dependence between H and L; b — of regression equation (5.6) expressing the dependence between S and L.

From the results of tests presented above it becomes clear that the minimum values of H for the d25 coal dust are only slightly higher than those for the d85 coal dust. In order to make sure that a proper safety margin is provided the values of H found for the d25 coal dust were not considered, of course, as affecting the definition of the firedamp fuse given at the end of Section 5.3.1.2 with reference to the d85 coal dust.

In practice roofs of workings only in exceptional cases have as even surface as they have in experimental galleries. The tests carried out were

of a fundamental character and, therefore, they had to be performed under strictly fixed roof conditions.

The limit thickness of the roof layer of methane, found under specified test conditions to equal 1 cm for the firedamp fuse, represents merely an approximate value; in practice, therefore, it ought to be interpreted sensibly.

Roof conditions present actually an unlimited number of varieties so that, when it is necessary to decide whether one is in the presence of a firedamp fuse, or of a roof accumulation of methane, capable of initiating a coal dust explosion, it is necessary to be rather careful in the evaluation of circumstances.

The conditions under which the tests were performed provided already a certain margin of safety in the determination of the limit thickness of the roof layer of methane; the roof accumulation of methane was formed by placing a paper diaphragm under the roof.

This diaphragm created a kind of a recess for methane in which both the velocity of the flame and the pressure of the blast were increased. It would have been better to give up the use of the paper diaphragm, yet, without it, the difficulties of controlling the concentration of methane and the thickness and length of the roof layer — in conditions of an underground experimental gallery — were practically insurmountable.

5.3.1.4. Practical conclusions from the results of investigations on the roof layers of firedamp and data obtained from measurements carried out in mines. Roof layers of methane, capable of initiating a coal dust explosion, represent a direct and very serious danger. Therefore, systematic inspections must be made for the purpose of detecting their presence. Such inspections, in particular, ought to be made in working with auxiliary ventilation with special attention to such places at which directly dangerous accumulations of methane behind the support are likely to occur.

The firedamp fuses which, by definition, are not able to initiate an explosion of methane, but are capable of rapidly transmitting the flame, constitute likewise a direct danger if they appear in connection with dangerous accumulations of methane behind the support. A firedamp fuse, ignited at any place whatever, will carry the flame to the methane accumulated behind the support and will certainly cause its ignition. Therefore, when a firedamp fuse is detected it is absolutely necessary to find out whether there is any connection with a dangerous methane accumulation behind the support. It should be noted, however, that in the majority of cases firedamp fuses are connected with methane accumulations since they both come into existence as often as not as a result of roof evolution of methane which was discussed previously.

According to investigations carried out in the *EM Barbara* the lengths

of separate methane accumulations behind the support may vary within wide limits [46]. In our instance the accumulation of methane was found to extend 1100 m in length. Concentrations of methane, according to these investigations, were sometimes as high as 100 percent.

The lengths of particular firedamp fuses may also vary within wide limits but, as a rule, these limits are not so wide as in the case of methane accumulations behind the support. In the majority of cases the length of firedamp fuses did not exceed 100 m.

The proportion between the lengths of firedamp fuses and the lengths of methane accumulations behind the support, expressed in percentages, varied from 9.5 to 100 percent the average proportion being equal to 50 percent [46].

Directly dangerous roof layers of methane, the same as firedamp fuses connected with dangerous accumulations of methane behind the support, are the more dangerous the nearer they are situated to places at which their ignition is very probable, such as the faces of workings where shotfiring or mechanical coal-winning operations are in progress. In the last-mentioned case the ignition of methane can be caused easily by friction.

Just as it is necessary to take protective measures in the case of the presence of dangerous accumulations of methane behind the support, so it is also necessary to take such measures when dangerous roof layers of methane or firedamp fuses, having a connection with dangerous accumulations of methane, cannot be immediately removed. The protective measures, referred to above, must be the more efficient the nearer to the face of a working the presence is detected of a methane accumulation or of firedamp fuses.

The velocity of the air in the working plays an enormous role in the problem of firedamp fuses, of dangerous roof layers of methane and of methane accumulations behind the support.

In a considerable majority of cases, if the velocity of the air current amounts to 1 m/sec or more, firedamp fuses and dangerous roof layers of methane are cleared away.

It ought to be stressed that firedamp fuses connected with methane accumulations behind the support present a more serious direct danger since in the open cross section of the working there are more factors which can initiate the ignition of methane than behind the support. Moreover roof accumulations of methane are in a direct touch with the air of the open cross section of the working which, doubtless, facilitates considerably the ignition of methane.

Roof layers of methane, as specified previously, always comprise a certain layer of an explosive mixture of methane which can be very easily ignited.

5.3.1.5. The minimum volume of firedamp in the form of a roof layer capable of initiating a coal dust explosion. One of the aims of the research work undertaken in the *EM Barbara* on the roof layers of methane had been the determination of the minimum volume of methane in the form of a roof layer capable of initiating a coal dust explosion.

According to the results of these experiments the minimum value of methane, found to be sufficient to initiate an explosion of the d85 coal dust, amounted to $V_{M\,min} = 1.5$ cu m, with $H = 5.2$ cm and $L = 40$ m. For the d25 coal dust it was found that $V_{M\,min} = 1.9$ cu m, with $H = 10$ cm, and $L = 20$ m.

If the experiments in question were more numerous it is possible that the values of $V_{M\,min}$ would have been found to be lower than those given above.

It would not be out of place to draw the attention of the Reader to the fact that, when the minimum value of H is arrived at through increasing the value of L then, as far as the value of $V_{M\,min}$ is concerned, its minimum is reached at a certain value of L but, thereafter, with the increase in the value of L the value of V also grows.

5.3.1.6. British investigations on the formation of firedamp roof layers and on the ways of their removal. In the British Safety in Mines Research Institute of Sheffield very valuable investigations were carried out on the formation of roof layers of methane and on the influence exerted by air velocities upon their removal [3]–[5], [110].

British research workers formulated recommendations about the way in which roof layers of methane should be controlled. These recommendations comprise the notion of what is called stratification numbers which make it possible to determine when the dispersion of such layers through ventilation, and the prevention of their displacement, can be accomplished efectively.

Examinations of the effectiveness of mixing with the air the firedamp evolving from the roofs of workings had demonstrated that the velocity of the air flowing through mine workings, measured as close as possible to the place of the evolution of firedamp, must exceed the limit value of the velocity capable of thoroughly dispersing the methane in the air thereby preventing the formation of dangerous roof layers of methane in the workings [5].

Bakke and Leach [4], [5], [110] supplied the following formula, applicable to conditions existing in mines in which ventilation is used, for determining the air velocity v_g in a gallery upon which depends the effective prevention of the formation of dangerous roof accumulations of methane

$$v_g = L\sqrt[3]{g \cdot \frac{\Delta p}{p} \cdot \frac{Q}{D}} = 8.19\sqrt[3]{\frac{Q}{D}} \text{ m/sec} \tag{5.7}$$

where

g — acceleration of gravity = 9.81 m/sec^2,

Δp — the difference between the mass density of air and that of methane amounting to 0.576 kg/cu m (methane density equals 0.717 kg/cu m),

p — the mass density of air, 1.293 kg/cu m,

D — the width of the layer of methane; for rectangular workings this width is measured under the roof; when the roof is vault-shaped the width of the layer is assumed to equal 3/4 of the width of the working measured in its broadest place in the inside diameter of the support,

Q — the strength of the source of methane, cu m/sec,

L — the stratification number.

When $L \geqslant 5$ firedamp fuses are not formed; when $L = 3$–5 there is already a probability of firedamp fuses being formed, and when $L < 3$ firedamp fuses are formed,

For the mine operation purposes it is assumed that $L = 5$.

The use of the formula (5.7) permits to verify the effectiveness of the ventilation under the presence of the methane hazard. The real velocity of the air v_{rz} in a working exposed to the hazard of the possible presence of dangerous roof accumulations of methane ought to exceed, or at least be equal to, the velocity v_g determined according to the formula in question. This means that

$$l = \frac{v_g}{v_{rz}} = 8.19\frac{\sqrt[3]{\frac{Q}{D}}}{v_{rz}} \tag{5.8}$$

where l denotes the ventilation effectiveness index; when $l > 1$ the ventilation is not effective enough since it does not prevent the formation of firedamp fuses; when $l \leqslant 1$ the probability of the formation of firedamp fuses is slight.

From the Bakke and Leach's formula it follows that the stratification of methane in a working depends in a much higher degree upon the velocity of the airflow than upon the magnitude of the evolution of methane. Therefore, durable layers of methane can be formed where the evolution of methane is very small.

When the value of the stratification number L is determined one becomes better oriented as regards the necessary procedure to be adopted, as this number indicates to what extent the velocity of the air in workings ought to be increased in order to lessen the danger of the roof layers of methane in the workings.

The phenomenon of the stratification of methane under the roof in workings, according to British investigations, may be considered as depending upon:

— inclination of the roof,

— the stratification number,

— the surface friction coefficient of the sidewalls in the working,

— the resistance coefficient for the air current flowing through the working.

When ascending air currents are used for ventilation the mixing of methane with the ascending air is weak at first. With the increase in the velocity of the air the mixing of methane with air becomes better. With the increase of the inclination of the working a higher velocity of the air in the working is necessary to attain a good mixing effect. When descending air currents are used for ventilation a layer of methane might even move in the direction opposite to that of the airflow. This can be prevented by maintaining sufficiently high velocities of the air in the working.

As a result of research work on models it was possible to determine the mean air velocities measured in the vicinity of the source of the emission of methane which immediately and effectively prevent the formation of roof accumulations of methane in workings.

5.4. THE DANGER OF THE IGNITION OF FIREDAMP BY FRICTIONAL SPARKING

The common factors which can cause the ignition of firedamp in mines are illustrated in handbooks [63], [69].

The purpose of the present section is to supplement the information concerning the danger of frictional sparking.

Frictional sparking constitutes a very serious danger as the means of the ignition of methane. Many a disaster has been caused by it. The danger of sparks existed from the time when the use of primitive tools had been introduced in the mining of coal or stone. The full recognition of this danger, however, dates only a relatively short time back.

The first explosion of methane, caused undoubtedly by frictional sparking, has been the disaster of the year 1786, at the *Wallsend* mine in Great Britain. The cause of the explosion had been the rubbing of a steel friction wheel against flint. This primitive device served to light the workings and was operated in a majority of cases by children. The beam of sparks produced by operating this device was considered to be a safe source of light.

Since that time the number of disasters caused by friction had been

very large. Unfortunately, in spite of the recognition of the danger of friction resulting from the research work carried out on this subject, the suppresion of it in the mining practice has made little progress.

From the thermic point of view sparks may be classified in two basic groups: the sparks whose thermic energy has for its source the mechanical energy alone, and the sparks in which the mechanical energy, responsible for their origin, initiates an exothermic chemical reaction that constitutes the essential source of the heat energy of the spark.

The following different grades of the danger of sparks in the presence of methane may be discerned.

The greatest danger comes from sparks produced by striking or rubbing a light alloy against the rusty steel.

Light alloys are used for obvious reasons in many mining machines, among other things, driller casings are made of such alloys. As a result of relevent tests it has been found that a driller weighing 16.3 kg in a casing of the elektron alloy (containing 92 percent of magnesium), falling from the height of 30 cm on a piece of rusty steel, ignites methane in 5 percent of the cases. When it falls from the height of 75 cm, 50 percent of cases produce the ignition. Likewise a driller in a silumin casing (88 percent Al, 10 percent Si), dropped from the height of 113 cm on rusty steel, ignites methane in approximately 8 percent of cases.

The ignition of methane becomes particularly easy when the surface of the rusty steel is locally covered by particles of a light alloy as a result of rubbing. When the place of the "smear" of this kind is struck with a tool of a relatively small weight and with very little energy the sparks produced are capable of igniting methane.

As the second in the order of the grade of danger the sparks should be placed produced by the rubbing or striking sandstone against steel or other metal.

As the third in this order ought to be placed the sparks produced by the striking or rubbing of steel against steel.

How great a danger comes from friction discussed here is evidenced by statistics illustrating the percentage share of ignitions attributed to frictional sparking in the total number of ignitions of methane registered in different countries [13], [14], [104], [128], [135], [137], [156], [171]. The pertinent schedules are given in Table 5.2.

The basic and the most comprehensive investigations on the danger connected with the occurrence of frictional sparking in the presence of methane were carried out in the *EM Barbara* by Łobejko [115]. His work had been preceded by researches made in the *EM Barbara* by Ciok [17].

A schedule of the more important parameters of impacts or frictions (Table 5.3), through which ignitions of methane were obtained under

laboratory conditions, is based on both Polish and foreign investigations [115]. The high ignition capacity of sparks produced by an impact of rusty steel against light alloys is explained by the "miniature" thermite reaction of a light alloy with the rust.

Table 5.2

Percentage Share of Methane Ignitions Attributed to Frictional Sparking (According to Statistics) in the Total Number of Methane Ignitions

Country	Period of time	Share of ignitions %
Great Britain	1936–1950	14.3
Great Britain	1951–1958	30.0
Great Britain	1959–1966	46.3
USSR (the Donetz basin)	1963–1969	29.8
USA	1952–1960	19.6

A light alloy, on account of possessing a lower melting point and the property of easily adhering to the rust, as a result of a relatively mild collision with, or of being rubbed against, rust leaves its particles deposited in the pores and other irregularities of the surface of the rust thus forming a "smear." To start a thermite reaction and produce sparks igniting methane a very low impact energy — about 0.9 J — is quite sufficient under the described conditions. An impact of a hammer of a mass of merely 200 g might produce the energy of this magnitude.

The danger created by smears of light alloys on rusty steel is particularly strong in methane mines on account of the fact that such smears (of very small surface areas) are practically unnoticeable and can retain their ignition capacity for a period of several months.

The sparks igniting methane through the thermite reaction can be produced, certainly, by a direct impact, the so-called fall impact, of a light alloy on rusty steel. Such instances are known in mining, for example, in the *Cannoch Chase* colliery (Great Britain, 1950). The accident was caused by a hand driller in a casing of light alloy dropped on a steel bar. The disaster in the *Minister Achenbach* colliery in the Federal Republic of Germany in the year 1968 (15 fatal casualties), where methane and coal dust exploded, is attributed to the impact of an aluminum alloy on a piece of rusty steel.

A light alloy deposits its particles on tools striking objects or elements made of the same alloy forming what are called accretions. When a tool with a light alloy accretion comes into collision with rusty steel only

Table 5.3

The Smallest Magnitudes of Parameters at which Methane Ignitions from Frictional Sparking Were Attained

Combination of materials	Free fall			Tool strokes			Friction		
	impact energy J	velocity m/sec	literature	impact energy J	velocity m/sec	literature	load N	velocity m/sec	literature
Mg alloy — rusted steel	49	2.4	[171]	—	—	—	—	—	—
Al alloy — rusted steel	136	4.1	[171]	—	—	—	—	—	—
A hand tool — a smear of the Mg or Al alloy on rusted steel	—	—	—	0.9	2.8	[115]	—	—	—
A smear of Al alloy on a hand tool — rusted steel	—	—	—	1.5	3.6	[115]	—	—	—
A smear of Mg alloy on a hand tool — rusted steel	—	—	—	2.0	4.2	[115]	—	—	—
Picks of a chain cutter — sandstone	—	—	—	—	2.4	[13]	—	—	—
Cutter picks of a drum shearer — sandstone	—	—	—	—	5.4	[115]	—	—	—
Pick axe — sandstone	—	—	—	about 150	<6.0	[14]	—	—	—
Soft steel (a rotating disk) — sandstone	—	—	—	—	—	—	3400	3.4	[115]
							133	20.4	[128]
Al alloy (a rotating disk) — sandstone	—	—	—	—	—	—	488	10.9	[115]
Soft steel — soft steel	—	—	—	—	—	—	2030	4.6	[135]
							147	27.0	[137]
Hardened steel — hardened steel	1660	8.4	[104]	247	about 15	[156]	—	—	—

a slightly higher impact energy, namely, 1.5 J, will produce sparks capable of igniting methane.

Under laboratory conditions the lowest examined heights of a free fall leading to the ignition of methane amounted, for the magnesium alloy, to 0.3 m (the impact energy being equal to 49 J) and for the aluminum alloy to 0.84 m (the impact energy amounting to 136 J).

The rise of the temperature of the contact area caused by the process of the sliding friction between two different alloys is usually limited by the level of the melting point of the more fusible alloy.

A direct collision between a light alloy and steel will probably not ignite methane as easily as a collision between a steel tool and steel when the place of the contact will touch either accretions or smears of light alloy which exert but slight influence on the primary temperature of the collision area. For, when there is a direct collision between light alloy and steel on which there are no accretions or smears the primary increase in the temperature is lower — on account of the melting of the light alloy; thus, the conditions are less favorable to the ignition of the thermite mixture, particularly as far as the aluminum alloy is concerned (the ignition temperature of the aluminum alloy being higher than that of the magnesium alloy).

In falling-weight tests the optimum angle of the impact is 50° — that is, much more than the optimum angle of the sliding impact of a hammer (7°); for, in the case of a fall the major part of the impact energy is consumed in the plastic strain. Theshare of the fall energy in the primary increase of the temperature in the place of the contact of an impact is low in comparison with that of the energy of a sliding friction.

In the light of the above statement it becomes clear why a higher impact energy is necessary to cause the ignition of methane through a direct impact of a light alloy on rusty steel than in the case of a sliding collision of a tool with rusty steel on which accretions or smears of a light alloy are present. In any case, the values of the pertinent fall energies are low in comparison with the impact energies which one must expect to be confronted with under conditions prevailing in underground mines.

Despite the lowest quantities of the energy of the ignition of methane in the cases in which thermite sparks are produced the largest number of the ignitions of methane has been registered as being caused by frictional sparking from the cutting and winning elements of cutters and combined cutter loaders. This fact is due to the regular work of these machines on an enormous scale, the cutting and winning operations in seams containing methane causing, as a rule, the evolution of large quantities of methane so that the machines, mentioned above, very often work in the presence of explosive mixtures. As a result the probability of the ignition of methane

through these machines must be greater than that of its ignition by casual thermite sparks.

In spite of the changes in the technology of the explosion of coal and in the percentages of the entire quantity of the extracted coal, falling to the share of the particular types of mining machines, the number of methane ignitions caused by these machines in certain countries (for example, in Great Britain) is increasing permanently. A majority of these ignitions were of a restricted nature, yet some of them ended in great disasters; in the *Cholditch* mine in Great Britain in the year 1937, 30 men lost their lives and in the *Easington* mine, also in Great Britain, in the year 1951 there were 83 fatal casualties.

Tests made in laboratories fully confirmed the possibility of the ignition of methane through the friction between cutter bits and sandstone. When steel is rubbed against sandstone the ignition of methane occurs after a layer of glazed rock becomes deposited on the steel, thereby facilitating the process of the abrasion of the sandstone substance.

The deposit of sandstone on the metal, in the above described form, is formed usually after the process of friction has been in progress a certain time. The formation of such a deposit is the more difficult the lower is the melting point of the pertinent metal. For in the beginning of the process of friction, especially in the case of metals or alloys the melting point of which is low, a contrary phenomenon occurs — that is, a layer of the metal is transferred onto the surface of the rock. However when, after a certain time, a thin layer of the glazed rock becomes deposited on the surface of the metal, it clings to the metal very strongly and then the ignition of methane may be caused very easily as a result of a short time of friction.

Through impacts on the sandstone with a pickaxe, the mass of which was 2.5 kg, ignitions of methane were obtained under laboratory conditions the strokes being repeated in a quick succession from a distance of about 30 cm. In these tests a sliding friction occurred between the top surface of the pickaxe and the sandstone the length of the slide being about 40 mm. As the result of this the impact energy, causing the ignition of methane, amounted to only 150 J.

Sparks produced by impact or friction of steel against steel are less dangerous from the viewpoint of the possibility of causing the ignition of methane. With fall impacts the ignitions of methane under laboratory conditions were effected only when hardened steel had been used of the hardness of at least 700 VDH.

Using a hardened steel plate, the surface of which was specially prepared (grooved), methane ignitions were achieved by dropping from the height of 3.6 m an object made of hardened steel the mass of which was

47 kg. The impact energy amounted in this case to 1660 J. When the steel plate was smooth the fall energy necessary for the ignition of methane amounted to 3920 J. Under special conditions the ignition of methane has been achieved by an impact of a hammer on a steel plate with the energy equal to 247 J.

While with the use of soft steel the ignition of methane by frictional sparking is considerably more difficult, yet it cannot be excluded when the velocities of the steel objects used for friction are considerable or when loads are big.

The problem of the danger of frictional sparking has been discussed here at some length on account of the growing hazard of the ignition of methane by such sparking in connection with the progress in the mechanization of minning operations. Besides, the information on the danger of frictional sparking contained in handbooks and even in periodicals is quite inadequate.

5.5. EFFECTS OF EXPLOSION INITIATORS UPON THE EXPLOSIBILITY OF COAL DUST

5.5.1. General information

When the hazard of coal dust explosions is being discussed in the coal industry it becomes often necessary to answer the simple question: is a given coal dust explosive?

In Chapters from 2 to 4 the dependence of the explosibility of coal dust upon numerous factors has been discussed.

Under specified conditions the possibility of an explosion of the explosive coal dust depends on the explosion initiator.

It is proper to stress here that the explosibility of coal dust is the term denoting its ability to propagate an explosion. As a nonexplosive coal dust, in the absolute sense of the adjective, should be regarded coal dust incapable of propagating an explosion under any possible conditions no matter what kind of an explosion initiator was used; in other words, even the strongest explosion initiators which, conceivably, could be used in mines — under the most favorable conditions for an explosion — should not be able to make such coal dust capable of propagating an explosion.

In spite of the great role of the explosion initiator the knowledge of its influence on the explosibility of coal dust is very limited outside the circles of those who are engaged in the study of the problem. This leads to certain misunderstandings and, frequently, even to errors in the evaluation of dangerous conditions.

5.5.2. Initiators used by foreign researchers

Individual research workers in their basic investigations used different initiators which makes it difficult, and sometimes impossible, to compare the results of their respective researches.

In France the pioneer of investigations on the explosibility of coal dust, Taffanel, used as his basic initiators:

limite 1 — 240 g of explosive gelatine,

limite 2 — 240 g of explosive gelatine with a 10 m zone of very dangerous coal dust of a concentration equal to 0.45 kg/cu m.

When *limite 1* had been used as the initiator the zone with the coal dust to be examined usually extended over the length of 30 m only, while with the initiator *limite 2* the corresponding zone was 90 to 100 m long.

According to Section 2.1.1 the degree of the explosibility of coal dust is expressed by the lowest percentage of the content in the dust of incombustible solid matter sufficient to make the dust incapable to propagate an explosion. This magnitude is denoted by the symbol S. The index of the explosibility is denoted by the symbol Z (Section 2.1.2).

Taffanel, as well as other investigators, determined different values of S depending on the initiator used. Taffanel, for example, found — in the case of the very dangerous dust — $S = 60$ percent when the initiator had been *limite 1*, and $S = 70$ percent when the initiator had been *limite 2*.

American research workers [141] used two kinds of initiators:

A — 4 pounds of black powder tamped in the mortar hole with 3 pounds of clay,

B — a charge of gunpowder as in the initiator A, and a zone 50 feet long of very dangerous coal dust of a concentration equal to 0.54 kg/cu m.

The length of the zone with the examined coal dust had been 350 feet in the main gallery and 300 feet in the parallel one. Tests were made in the *Bruceton* experimental mine. For coals containing more than 25 percent of volatile matter the values of S were found to be from 55 to 67 percent when the initiator A, and 65 to 82 percent when the initiator B, was used.

In Great Britain at first [142] 20 or 28 ounces of gunpowder, tamped with one pound of coal dust in the mortar hole, were used as the explosion initiator. In front of the mortar what is called *impetus tube* was fixed, 26 feet in length and 1 foot in diameter, into which about 2 pounds of the examined dust were fed. For coals containing more than 33 percent of volatile matter the values S were found to be about 67.5 percent. It should be noted that all the values of S given above refer to stone dusts of nearly the same efficiency.

Table 5.4

Parameters Characterizing the Initiators of Coal Dust Explosions

Explosion parameters	Distance from the face	Type of the initiator									
		methane, concentration ca. 9.5%						coal dust PI and PII			
	m	4* cu m	25 cu m	50 cu m	100 cu m	150 cu m	200 cu m	4mPI	4mPII	15mPII	30mPII
Maximum range of the flame, m		30–31	20–30	30–40	70–80	80–90	110–120	20–30	20–30	80–90	90–100
Maximum mean velocity of the flame, m/sec		35.6	95	233	471	441	580	60	78	130	340
Mean velocity of the flame, m/sec		18.1	70	164	204	197.6	203	31	36.4	62.7	163
Maximum (mean) static pressure, kN/sq m	20	16.0 (10.5)	87.5 (46.7)	165.0 (132.9)	322.5 (277.4)	562.0 (452.8)	700.0 (588.5)				
	40	14.0 (8.0)	45.0 (31.4)	82.5 (52.5)	62.5 (48.0)	117.5 (66.8)	155.0 (143.0)				
	60	24.0 (14.6)	32.5 (25.3)	120.0 (104.6)	167.5 (137.5)	237.5 (173.5)	337.5 (248.5)				
	80	— —	30.0 (2.25)	90.0 (70.4)	110.0 (85.9)	182.5 (86.1)	207.5 (173.0)				
	120	1.0 (1.0)	32.5 (22.1)	87.5 (68.7)	122.5 (92.2)	137.5 (115.6)	192.5 (154.4)				
	160	4.0 (2.4)	42.5 (33.2)	87.5 (75.3)	150.0 (117.8)	150.0 (139.9)	232.5 (194.0)				
	200	8.0 (4.0)	12.5 (11.4)	45.0 (38.7)	70.0 (48.7)	85.0 (57.8)	100.0 (83.5)				

Table 5.4 (continued)

	240	8.0	19.0	15.0	50.0	42.5	55.0				
		(3.33)	(11.3)	(13.3)	(22.8)	(26.7)	(30.5)				
	280	2.0	30.0	40.0	50.0	170.0	125.0				
		(1.5)	(19.3)	(22.1)	(31.5)	(80.0)	(95.0)				
	320	1.0	10.0	12.5	40.0	15.0	125.0				
		(1.0)	(8.6)	(10.4)	(16.8)	(14.3)	(22.0)				
	360	2.0	20.0	35.0	47.5	62.5	75.0				
		(2.0)	(15.4)	(32.9)	(40.9)	(55.0)	(62.5)				
	400	1.0	10.0	10.0	15.0	12.4	15.0				
		(1.0)	(9.5)	(8.8)	(10.9)	(11.4)	(14.0)				
Dynamic pressure, kN/sq m		0.17	2.93	15.2	50.68	48.21	49.16	0.51	0.71	2.53	15.2
Blast velocity, m/sec		16.4	63.2	120.0	170.9	166.4	169.8	24.4	32.1	59.16	120.0

*Thirty-meter methane roof layer.

Later on, British research workers began to use a new initiator in the form of a kind of a rocket. It consists in the firing of a charge of 20 ounces of gunpowder which shoots out from a special receptacle and ignites 4.5 pounds of dangerous coal dust. This initiator works very mildly, as far as the blast is concerned, but it acts very efficiently as an igniter of coal dust [158].

5.5.3. Standard initiators of coal dust explosions used in the *EM Barbara*

In the *EM Barbara* more attention was paid to investigations on the effect of the initiator upon the explosibility of coal dust because of the fundamental, as well as the practical, importance of these investigations. Thus, very many experiments were made and many kinds of what are called standard initiators, and of other initiators, had been used in these experiments. In the *EM Barbara* the initiators, which had been used in numerous series of experiments, were classified as standard initiators. They were described in Section 3.4.3.

The standard initiators were not the only means of initiating coal dust explosions employed in the *EM Barbara* in the diverse research works conducted there. In many experiments, carried out in the 400 m gallery, the initiators used were 100, 150 and 200 cu m of CH_4. The concentrations of methane had been 8 to 9.5 percent. In the experiments described in Section 5.4.4 the explosion of coal dust has been initiated by the ignition of a roof layer of methane. Besides, many other methods of initiating coal dust explosions were used, described in the original publications. In Fig. 5.7 diagrams are shown representing flame velocities recorded with reference to standard initiators in the 200 m and 400 m experimental galleries.

Table 5.4 gives the fundamental data concerning the initiators used in the *EM Barbara*, namely, the range of the flame, the minimum velocity of the flame, the dynamic and static pressures, and the velocity of the blast. The dynamic and static pressures given in Table 5.4 are theoretical values calculated on the basis of the mean velocities of the flame.

5.5.4. Investigations on the effects of the standard initiators on the explosibility of coal dust

With the use of standard initiators the explosibility of the d85 *Barbara* coal dust and of the d25 coal dust has been determined. The tests were carried out under conditions ensuring the easiest dispersion as well as under the most difficult conditions of dispersion. In the outcome the

values of S and Z were determined with reference to the initiators in question. The results of these labor consuming tests, carried out in the 200 m gallery, are scheduled in Table 5.5 (in this table the letter N denotes the nonpropagation of the explosion). For the sake of accuracy it ought to be explained that the values given in Table 5.5 have been slightly corrected, on the basis of further tests, in comparison with those published in the work [24].

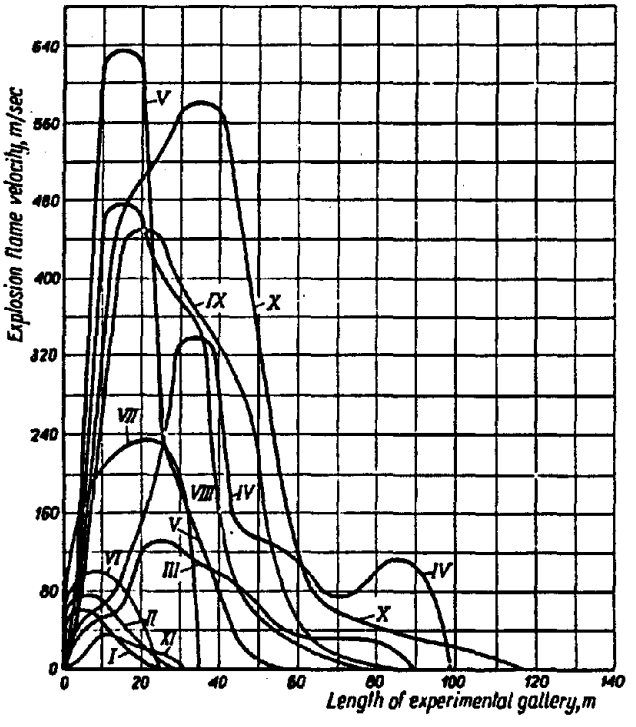


Fig. 5.7. Diagrams of flame velocities in the cases in which standard initiators were used in experimental galleries: the 200 m gallery: *I* — 4md25, *II* — 4md85, *III* — 15mPII, *IV* — 30mPII, *V* — 50 cu m CH_4; the 400 m gallery: *VI* — 25 cu m CH_4, *VII* — 50 cu m CH_4, *VIII* — 100 cu m CH_4, *IX* — 150 cu m CH_4, *X* — 200 cu m CH_4, *XI* — 30 m long roof layer of methane 4 cu m in volume.

As can be seen in Table 5.5 the initiators 15mPII and 50 cu m CH_4 9.5 percent are almost equally efficient; the differences between the values of S as well as of Z are quite small. In the case of the $d85$ dust, under the easiest dispersion conditions, the influence of the strength of the initiator upon the value of S is evidently one of a relatively very small significance. What actually happens is the simultaneous influence of dispersion conditions and of the dispersibility of the coal dust. Nonetheless, even in the case of the $d85$ dust — under the easiest dispersion conditions — the dif-

ferences between the initiators are noticeable; more noticeable, of course, when the relevant value of Z is being compared.

With the use of direct initiator the values of S are, naturally, the lowest; they are the highest when the initiator 30mPII is used. The following initiators ought to be regarded as strong: 30mPII, 15mPII and 50 cu m CH_4. There is a relatively slight difference between the last two initiators. The initiator 30mPII has the distinction of being very strong.

Table 5.5

Results of Investigations Carried out in the 200 m Experimental Gallery on the Dependence of the Explosibility of Coal Dust upon the Standard Initiators

Initiator	Dust $d85$ — dispersion conditions				Dust $d25$ — dispersion conditions			
	easiest		most difficult		easiest		most difficult	
	S	Z	S	Z	S	Z	S	Z
Direct	72.5	2.63	47.5	0.905	37.5	0.60	N	0
4mPII, PI	75	3.00	60	1.50	45	0.82	N	0
15mPII	80	4.00	77.5	3.44	70	2.33	62.5	1.67
30mPII	87.5	7.00	(82.5)	(4.71)	75	3.00	70	2.33
50 cu m CH_4	80	4.00	(77.5)	(3.44)	72.5	2.63	60	1.5

Note: N signifies that no propagations of explosions have occurred.

Under conditions of the most difficult dispersion of the $d85$ dust the influence of the initiator is very clearly discernible. The lowest value of S, determined with the use of the direct initiator, increases very materially when the initiators 4mPII and 15mPII are used. The very big differences recorded here are caused by the differences in the magnitude of the concentration and motion of the primary cloud.

In the case of the weak — that is, of the direct and the 4mPII initiators, very marked differences are noted between the values of S depending on the differences between the easiest and the most difficult dispersion conditions. When strong initiators are used these differences become obliterated. This is comprehensible when the great force of the blast, produced by these initiators which raises very big primary clouds, is considered.

In the case of the $d25$ dust, when dispersion conditions are the easiest, the influence of the initiator on the value of S is very marked. The increase in the value is very high with the passing from the direct initiator to strong initiators. Under conditions of the most difficult dispersion the $d25$ dust is incapable of propagating an explosion when the direct or the 4mPII initiator is used, even with the natural content in the dust of incombustible solid matter. This shows that the primary cloud, raised by the firing of gunpowder, on being ignited does not produce a blast of an

energy sufficient to raise secondary clouds of a size and concentration required to develop the flame. The same dust, when the initiator used was 15mPII, required already 62.5 percent of incombustible solid matter to be made incapable of propagating an explosion. The above facts illustrate quite well the enormous influence exerted by the explosion initiator and the conditions of dispersion on the explosibility of coal dust.

With weak initiators, and under difficult dispersion conditions, the same dust proved to be altogether inexplosive which, under the same conditions but with the use of strong initiators, exhibited very strong explosive properties.

Unfortunately there is no certainty in the practice of mining that a strong initiator will not disclose its presence in mine workings. The dust, found to be incapable of exploding when weak initiators are used, cannot be regarded as safe under conditions existing in mines if it is able to propagate an explosion when a strong initiator comes into play.

As an illustration of the influence exerted by each of the three standard initiators upon the explosibility of the d85 coal dust — with the incombustible solid matter content $n = 70$ percent and under the easiest dispersion conditions — a diagram is given in Fig. 5.8a showing the velocity of the flame of three explosions: No. 1528 in which the direct initiator had been used; No. 770 with the 4mPII initiator; and No. 756 with the 15mPII initiator. From this diagram the explosion was left out in which the very strong 30mPII initiator had been used on account of its violent development under the described conditions.

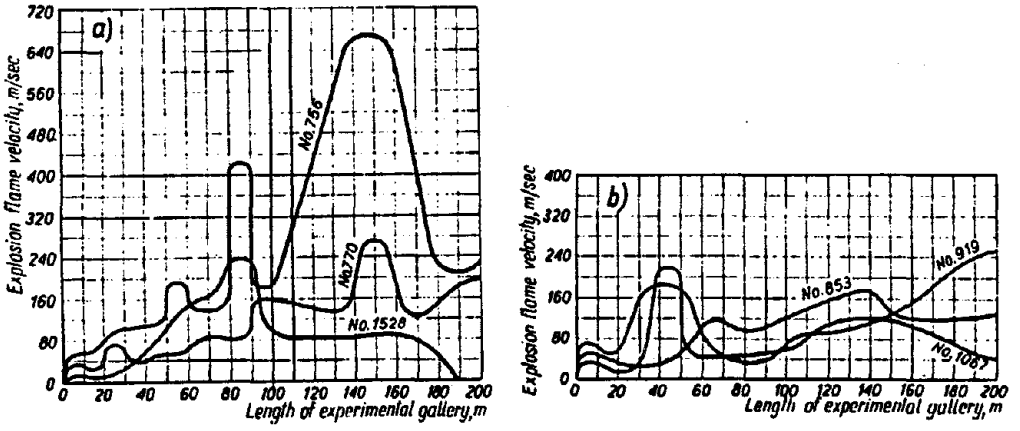


Fig. 5.8. Diagrams of flame velocities of the d85 coal dust explosion flame: a — n = = 70%, the easiest dispersion conditions, initiators: explosion No. 1528 — direct; explosion No. 770 — 4mPII; explosion No. 756 — 15mPII; b — the most difficult dispersion conditions; explosion No. 1067: $n = 45\%$, direct initiator; explosion No. 853: $n = 50\%$, initiator — 4mPII; explosion No. 919: $n = 75\%$, initiator 15mPII.

For the purpose of illustrating the differences between the strengths of the initiators, under conditions of the most difficult dispersion of the $d85$ dust, in Fig. 5.8b are given graphs representing the velocities of the flame of three explosion: No. 1067, No. 853 and No. 919 in which the direct initiator and the initiators 4mPII and 15mPII were used, respectively. In all of the above graphs the courses of the relevant coal dust explosions refer to conditions in which the contents of the incombustible solid matter in the dust had been close to the limit values. When these values were increased by 2.5 or 5 percent the explosions were no longer propagated. As can be seen in the above graphs for the values of $n = 45$ percent up to $n = 75$ percent the explosions take a mild course, and flame velocities are low.

5.5.5. Initiation of coal dust explosions directly by shotfiring operations

At the time when blasting powder or explosives not safe enough in the presence of coal dust had been used in mines, ignitions of coal dust directly by shotfiring operations were relatively frequent and they caused many disasters. After the introduction of permitted and coal mining explosives during the period of time following World War I the instances of coal dust being ignited by shotfiring operations, in which these explosives were used, became very rare. During the period between the wars there was only one case recorded in Poland of a coal dust explosion caused by the use of the coal explosive and no such cases occurred in our country after World War II.

On account of the fact that shotfiring synchronizes the raising of a cloud of coal dust at the face of the workings and the appearance there of detonation products, explosives that are not sufficiently safe in the presence of coal dust, or which are faulty in any respect, are very dangerous. In this connection of considerable importance is also the fact that, at the face of workings, the presence of dangerous coal dust is quite common in contrast to the presence of the explosive mixture of methane.

In the *EM Barbara* tests were made on a very large scale for the purpose of determining the degree of the safety of permitted explosives in the presence of coal dust. These tests proved a very high degree of safety of such explosives when used in coal, and they led to the finding of conditions which are the most dangerous for firing shots. The tests in question and their results are described in works [29], [30], [34], [35], [41], [47], [69].

As regards the ignition of coal dust by rock explosives in order to illustrate the influence of the degree of fineness of coal dust on the ease

with which it can be ignited, in Table 5.6 is given a summary of the results of tests carried out in the *EM Barbara* under conditions of the most difficult dispersion of coal dust — that is, when this dust was distributed only on the floor of a surface gallery [24].

Table 5.6

A Schedule of the Limit Charges of Ammonite 5 Not Igniting Coal Dust from the *Barbara* Seam

Content of the fraction 75 μm in coal dust %	The limit (not igniting) charge of Ammonite 5 in a mortar g
13.4	350
25.2	300
85	200
100 ("powder")	50

The ignition of coal dust by a rock explosive is greatly facilitated, however, when a cloud of coal dust has been raised previously which is a normal situation when the method of delayed shotfiring is employed. Under such conditions, 10 g of Ammonite 5 are sufficient to ignite fine coal dust. The presence of coal dust in the shothole also greatly facilitates its ignition.

When any kind of a rock explosive is used in the presence of coal dust it may easily come to the initiation of an explosion since rock explosives produce a flame of a sufficiently high temperature and of a duration sufficiently long to ignite a cloud of coal dust. On account of this, rock explosives are not permissible in coal mines. Neither should they be used in works in which shotfiring operations are performed in coal-and-rock roadways.

It happens, however, that rock dynamites or ammonites are used by permission of mining authorities for shotfiring in stone in the vicinity of coal dust, for example, when it becomes necessary to force the roof caving. A necessity of this kind occurs relatively often when the mining of coal is effected by the longwall working. In such cases shotfiring, with the use of rock explosives, is done in the presence of the dangerous coal dust in the working. It becomes necessary then to make certain that coal dust is removed from the area within a radius of at least 5 m from the shothole and replaced by limestone dust in such amount as is necessary to bring the content of the incombustible solid matter in the dust of working to be not lower than 90 percent. Moreover, limestone dust ought to

cover closely the whole surface of the working within the radius of 5 m from every shothole.

Rock dynamites and rock ammonites are not at all the only rock explosives used in mining. In particular, it is necessary to remember that detonating fuses and sharp electric detonators belong to the category of rock explosives. The core of a detonating fuse always contains a rock explosive such as, for example, pentrite. The primers in sharp electric detonators contain a charge of a rock explosive such as trotyl (TNT), tetryl, pentrite and lead azide.

A detonating fuse can easily cause the ignition of coal dust even if used in pieces only a few cm long. The initiation of a coal dust explosion is particularly easy when the fuse in coils is fired in the vicinity of coal dust. Likewise several sharp electric detonators, fired simultaneously on the outside of a shothole, can ignite a cloud of coal dust. Improper use of rock explosives has led many a time to serious accidents.

Miners rather unwillingly use the detonating fuse though this is obligatory in deeper shotholes to ensure the complete detonation of the charge. It happens at times that they destroy whatever is left of the fuse by firing it on the floor of the working. Such proceedings caused two explosions of coal dust: in the *Sośnica* mine in the year 1965 and in the *Szczyglowice* mine in the year 1972. Only by a happy coincidence no lives were lost in these explosions; the miners involved suffering only from burns.

Much worse were the effects of an accident that happened in the *Walenty Wawel* mine in the year 1967. An explosion of coal dust had been initiated in a shortwall working as the result of the use of rock dynamite for knocking out the support. For this purpose 10 kg of dynamite were fired in a single series. In consequence the explosion of coal dust traveled a distance of altogether 350 m until it was stopped by stone dust barriers. Four men were killed in the accident. In the shortwall working in question, and in the neighboring longwall working, no dusting with stone dust has been practiced this being not required normally by regulations. Under these conditions it has been possible for the explosion of coal dust to develop. Of course the firing of the rock dynamite is allowed only in tamped shotholes and it was the duty of the shotfirers to remove coal dust from the neighborhood of the shotholes and to dust the place with stone dust.

In view of the serious danger connected with the firing of rock explosives in the vicinity of coal dust and considering the possibility of errors being commited in shotfiring operations — not to mention the unusual blunders described above by way of examples — it is imperative to carry out shotfiring operations with rock explosives in the presence of coal dust exclusively under the supervision of authorized inspectors.

5.5.6. Effects of large charges of explosives and of delay shotfiring on the explosibility of coal dust

With all initiators discussed in Sections 5.5.3 and 5.5.4 for the initiation of a coal dust or methane explosion a charge of 750 g of gunpowder had been used.

In practice, even in relatively narrow faces, the charges used jointly many a time exceed 10 kg. The likelihood of raising a cloud of coal dust with such large charges is very great. It should be mentioned also that a large number of shotholes fired simultaneously at the face or with millisecond intervals, will raise coal dust practically from the whole cross section of a working. Delay shotfiring is a special initiator with which the conditions of initiating an explosion are particularly advantageous as has been explained in Section 5.3.1.5. The influence of such initiators on the explosibility of coal dust has been examined. The tests, described in the publication [24], demonstrated that delay shotfiring may have effects equal to the effects of exploding 50 cu m CH_4 or 15mPII, naturally under the provision that one of the fired explosive charges will be capable of igniting a' cloud of coal dust. This fact should be well kept in mind when it is intended to fire a large number of shotholes in a single series. This is particularly important when one takes into consideration the fact that — as has been demonstrated by tests previously referred to [34] — the ease with which coal dust can be ignited becomes more pronounced with the increase in the size of the charge. The safety of shotfiring under these conditions depends, to a decisive degree, upon the margin of safety on which one may count using a particular explosive in the presence of coal dust.

5.6. COAL DUST EXPLOSION IN THE CASE OF THE FORMATION OF A DANGEROUS COAL DUST CLOUD AND ITS IGNITION BY VARIOUS FACTORS

Quite small quantities of the electric energy suffice to ignite a dangerous cloud of coal dust. Therefore if in a dangerous cloud of coal dust a thermic factor appears, even one possessing but a small energy, an explosion of coal dust can occur quite easily. Such conditions, unfortunately, are quite possible in mines, a fact of which the administration of mines is not always well aware. For instance, conditions of this kind may be brought about by an accidental derailment of cars loaded with fine coal or even with coal if the cars move with considerable speed. Coal dust can be raised from the cars or as the result of the overturned cars colliding with the floor or the support of the road. If in the working in question

there are cables, or braided wires present, a derailment of cars can easily produce a short circuit arc which will easily ignite a cloud of coal dust. Such a disaster happened in the *Łagiewniki* mine in the year 1956. Eight miners lost their lives in this disaster and six miners suffered injuries. For the sake of accuracy it should be explained that in this particular case the ignition of coal dust could have been caused by a short circuit arc produced in a damaged cable or by open light which had been in use at that time in mines containing no methane.

In the year 1963 an enormous disaster occurred in the Japanese mine *Mikawa* when 458 miners were killed. As a result of a breakdown of joints between cars and the latter rolling down a descending gallery at a dangerous speed a cloud of coal dust was raised in the gallery. In the descending gallery a belt conveyor was situated the same as in the *Łagiewniki* mine. In both cases the workings contained large quantities of very dangerous coal dust. According to the conjecture made by a commission appointed to investigate the disaster in the *Mikawa* mine the ignition of the cloud of coal dust could have been caused either by short circuit arc in a damaged cable, or by frictional sparking.

The two disasters described above illustrate, in the most convincing manner, the tremendous hazard which attaches to accumulations of dangerous coal dust in areas of methane and even situated far away from the places of shotfiring operations.

The need of special regulations on the suppression of such hazards is obvious. It should be noted that the disaster in the *Łagiewniki* mine, as well as that in the mine *Mikawa*, happened in spite of the fact that the binding regulations were adhered to.

For the sake of being accurate it is proper to add that the above disasters are mentioned here only by way of examples. Similar accidents, under diverse mining conditions, were actually much more numerous.

6. THE DEPENDENCE OF THE COURSE OF AN EXPLOSION UPON THE DISTRIBUTION OF COAL DUST IN THE WORKINGS, UPON THE DIMENSIONS OF THE WORKINGS, THE LENGTH OF ZONES, THE DIRECTION OF THE DEVELOPMENT OF EXPLOSIONS AND UPON THE CONTENT OF FIREDAMP IN THE AIR OF THE WORKINGS

6.1. EFFECTS OF THE SURFACE LAYERS OF COAL DUST UPON THE COURSE OF AN EXPLOSION

6.1.1. Comparison of the conditions under which the classical basic experiments were carried out on the explosibility of coal dust with the conditions prevailing in mines

All the experiments discussed in the foregoing chapters were carried out with uniform (homogeneous) mixtures of coal dust with stone dust. In basic investigations this was necessary. In the mining practice one deals usually with the dust of a diverse composition as regards both its fineness and the content in its particular layers in workings of the incombustible solid matter. This fact is of tremendous importance to the course of explosions.

In the experiments described in this chapter, throughout the entire examined zone, likewise the same kind of coal dust has been distributed — that is, the dust of a uniform degree of fineness and of an equal content of incombustible solid matter. This dust was evenly distributed over the entire zone under examination. Two entirely contrasting dispersion conditions were created intentionally by placing coal dust either on the floor of the gallery or on the roof bars and shelves.

Experiments had to be conducted in this manner in order to make possible a systematic examination of the influence of particular parameters on the explosibility of coal dust. This method offered the possibility of drawing generalizing conclusions to which, as a matter of principle, all systematic research works must aspire.

In the mining practice the conditions of dustiness in workings are far from such a uniformity; on the contrary, they vary considerably.

The above remarks should not be interpreted as a suggestion that the basic investigations, described in this book, have no relation to reality and that conclusions drawn from their results do not possess the value ascribed to them. Actually these investigations supply the facts on which reliable practical conclusions can be based. Nevertheless the basic investigations ought to take into account, as far as possible, the most characteristic conditions existing in mines. The basic investigations which had been carried out — accompanied by as thorough a study as possible of conditions prevailing in mines with regard to the hazard inherent in the presence of coal dust — helped to work out the means of limiting effectively, and even of preventing, the danger of coal dust explosions. These means will be discussed in the following chapters.

Conditions existing in mines are greatly varied so that their comprehensive study would require a great expenditure of funds and would take a very long time. However, even now, the investigations carried out so far in different countries make it possible to introduce effective measures against the danger of coal dust explosions.

6.1.2. The composition of the dust cloud during coal dust explosions in mines

As was mentioned previously the layers of coal dust accumulated in mine workings, in a considerable majority of cases, are not uniform in respect of the fineness of the dust, the content of incombustible solid matter and the content of free water.

During an explosion of coal dust in a mine not all of the dust accumulated in a working is raised to the air. The same happens under the conditions in which experiments are carried out with the exception of special experiments, made for the purpose of determining the limit of the explosibility of coal dust, which were discussed in Chapter 4.

Undoubtedly the decisive role in an explosion of coal dust in a mine is played by the cloud of coal dust raised to the air and dispersed throughout the cross section of the working. The composition of this cloud would be found to correspond strictly to the composition of coal dust, accumulated in the working, only when a uniform coal dust is accumulated in the entire cross section of the working without forming layers of varying compositions.

Such phenomena practically do not occur in mines.

During an explosion of coal dust the blast preceding the flame raises the dust mainly from the surface layers, and the highest proportion of the dust raised comes from the upper parts of the cross section of the working on account of the fact that this dust is the easiest to be raised

to the air. Only when very strong explosion initiators come into play, in the form of a large accumulation of an explosive mixture of methane or when the further development of the explosion is very violent producing a very strong blast, the dust is raised to the air relatively evenly from the whole cross section of the working; even then, however, not the whole accumulations of dust are being raised.

In summing up the above explanations it should be underlined that in mines the surface layers of dust, and particularly its accumulations on the support, on pipes and the upper parts of the cross section of workings, are of decisive importance with regard to the course which an explosion of coal dust will take. Apart from the surface layers an important role is also played, obviously, by the distribution of the dust in the cross section of workings.

6.1.3. The raising of coal dust during an explosion

Special experiments were carried out in the experimental galleries of the *EM Barbara* for the purpose of ascertaining the quantities of dust raised from roof bars and from the floor during an explosion.

Directly after an explosion a flow of air takes place in the gallery which also raises certain quantities of the dust. When explosions are rather weak the same phenomenon occurs on a smaller scale and, therefore, the experiments in question were made under conditions determined by rather weak explosions.

In the course of fixing the value of S for the d85 dust from the seam 416, 25 cu m CH_4 being used as the initiator, the quantities of dust raised from roof bars were determined in the experiments in which explosions were propagated as well as those in which no propagation occurred. The results of these investigations are presented in Table 6.1.

After the fading away of the direct influence of the initiator the quantity of the dust raised to the air from the roof bars grows until all

Table 6.1

Percentages of Coal Dust Raised from Roof Bars by Propagated and Not Propagated Explosions

Explosions	Percentages of coal dust raised from roof bars located at the distance from the gallery's face of m:									
	11.5	21.5	31.5	41.5	51.5	61.5	71.5	81.5	91.5	98.5
Propagated	61	82	77	72	84	79	97	95	100	100
Not propagated	56	74	68	59	74	71	93	83	97	100

the dust has been thrown down from them. The quantities of the dust, raised from the roof bars up to a distance of about 90 m from the face of the gallery, were smaller when the explosions had not been propagated than the corresponding quantities when the explosions were propagated.

Analogous investigations were made on the quantities of dust raised from the floor of galleries. The results are listed in Table 6.2. It can be seen that the quantities of the dust raised from floors are considerably smaller than those raised from roof bars. The influence of the nonpropagation of explosions on the raising of the dust from floors is more evident from the Table 6.2.

Table 6.2

Percentages of Coal Dust Raised from the Floor by Propagated and Not Propagated Explosions

Explosions	Percentages of coal dust raised from 1 m of the floor; measurement points situated at the distances from the gallery's face of m:			
	10	30	50	100
Propagated	38	29	38	65
Not propagated	31	24	25	39

The experiments in question were carried out in the 140 m gallery. They were supplemented by investigations carried out on a considerably larger scale in a gallery 400 m long the cross section area of which was 7.5 sq m. Making use of the 30mPII initiator the quantities were determined of the $d85$ and of the $d25$ dusts raised from roof bars, both when an explosion had been propagated and when the flame had faded away before it traveled the whole distance of 400 m. In the latter case the range of the explosion varied from 280 to 360 m. The course of explosions was regulated by adding limestone dust. The content of the incombustible solid matter in the dust, on the whole, was close to the value of $S.$,

The results of twenty experiments are listed in Table 6.3.

The quantities of the raised dust are given in all tables in percentages.

The most interesting is the data on the raising of dust after the fading away of direct influence of the initiator. In the case of the experiments, the results of which are presented in Table 6.3, the influence of the initiator faded away at a distance of about 100 m from the face of the gallery. In view of this fact the zone of the first 100 m is left out from the data

Table 6.3

Results of Investigations on the Quantities of Coal Dust Raised from Roof Bars at Various Distances from the Face of the 400 m Experimental Gallery

Type of dust	q kg/cu m	Explosion	Distance from the gallery's face, m:															
			100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
			mean quantity of coal dust raised from roof bars by explosions, %															
*d*85	0.9–1.2	*N*	36.0	40.3	42.8	48.0	52.8	55.6	62.2	63.3	65.0	68.5	80.3	71.4	67.7	83.5	88.9	95.1
*d*85	1.0–1.2	*P*	80.2	91.9	85.2	83.0	80.1	87.0	83.4	83.2	85.0	89.3	83.6	83.4	87.8	94.7	94.0	99.0
*d*25	1.0–1.75	*N*	44.7	47.2	49.5	46.5	51.9	57.8	63.8	62.6	72.6	74.6	74.2	71.9	76.7	88.3	87.5	95.8
*d*25	1.5	*P*	49.5	49.3	53.4	47.6	53.9	55.7	62.9	58.1	68.1	68.0	76.0	coal dust zone extended up to 300 m only				

included in Table 6.3. In this table the propagated explosions are marked *P* and nonpropagated are marked *N*.

The results of the experiments, which are listed in Table 6.3, are presented in a graphic form in Fig. 6.1.

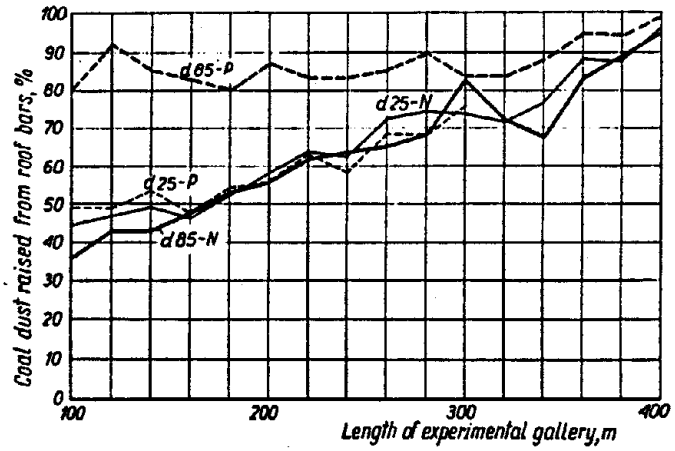


Fig. 6.1. The quantity of the *d*85 and *d*25 coal dusts raised from the roof bars depending on the distance from the face of the 400 m experimental gallery.

The following remarks may serve as the summing up of the results of the experiments in question:

— A propagated explosion raises from the roof bars much larger quantity of fine dust than an explosion that is not propagated.

— A propagated explosion raises from the roof bars more than 80 percent of the dust and this proportion undergoes only slight fluctuations and shows only a slight increase as the distance from the face of the gallery grows.

— As regards the explosions that were not propagated the quantities of the *d*85 dust, raised from roof bars, increase very noticeably as the distance from the gallery's face grows. The difference between the amounts of the *d*85 dust, raised to the air from roof bars by a propagated and by a nonpropagated explosion, diminishes with the increase in the distance from the face of the gallery.

— In the case of the *d*25 dust no major differences were found between the quantities of the dust raised from roof bars by a propagated and a nonpropagated explosion. Both kinds of explosions raise the dust from roof bars in noticeably increasing quantities as the distance from the face of the gallery grows.

— On the whole the quantity of the *d*25 dust raised from roof bars is markedly smaller than the corresponding amount of the *d*85 dust.

6.1.4. Examinations of surface layers of coal dust

In the *EM Barbara*, as well as in other scientific research institutions, studies were made on the role played by the surface layers of coal dust.

When studying the hazard presented by surface layers of coal dust in mine workings particular attention should be paid to the fact that the accumulation of coal dust in workings is a continuous process, while the efforts to suppress the hazard of the propagation of coal dust explosions — by means of dusting the workings with stone dust — are undertaken periodically. In consequence pure coal dust is usually discovered on the surface of workings particularly in such places in which it deposits itself intensively.

According to the results of examinations carried out in the *EM Barbara* [31] in cases in which the pure *d*85 coal dust deposits itself on a stone dust in the entire cross section of a working, when the explosion initiator used is 50 cu m CH_4, the explosion will be propagated even if the general percentage of incombustible solid matter in the working $n = 90$ percent. With the same initiator a mixture of coal dust with stone containing 80 percent of incombustible solid matter is safe as far as the propagation of an explosion is concerned.

When the surface of a working is covered with the *d*25 coal dust the hazard is somewhat smaller but still — in order to be on the safe side as far as the propagation of an explosion is concerned — the general content of incombustible solid matter n in the working should amount to 75 percent — that is, 2.5 percent more than would be necessary in the case of a mixture of stone dust with coal dust. The results presented above coincide almost strictly with the results obtained by British research workers [100].

A layer of pure coal dust less than 0.11 mm thick is capable of propagating an explosion in a gallery the cross section of which equals 7.7 sq m. This shows the hazard one is faced with in mines. The details concerning the manner in which coal dust sets in layers over stone dust, and the other way round, will be expounded when the effectiveness of the dusting of workings with stone dust will be discussed.

According to the data collected by the *EM Barbara* in the working, in which the dusting with stone dust is obligatory, the surface layer — up to 2 mm thick — contains on the average about 10 percent less of incombustible solid matter than the deeper layer. However, there are workings in which this difference reaches as much as 60 percent.

It ought to be repeated that the above data refers to zones in which the dusting with stone dust is obligatory.

6.2. THE EFFECT OF THE DISTRIBUTION OF DANGEROUS COAL DUST IN THE CROSS SECTION OF THE WORKINGS UPON THE HAZARD OF A COAL DUST EXPLOSION

6.2.1. The phenomenon of "separate" coal dust clouds

As has been mentioned before the quantity of the dust, as regards the degree of its fineness and the content of incombustible solid matter, may vary within the cross section of a working under the conditions existing in mines. With a view to determining how these conditions affect the possibility of an explosion being propagated, there were carried out in the *EM Barbara* broadly conceived investigations in which coal dust and stone dust had been distributed separately [31]. Thus conditions were created contrasting in the extreme with those which exist in mines, but a very clear picture was obtained of the effects of an irregular distribution of various dusts within the cross section of the working.

When one of the dusts is distributed on the floor and the other in the upper part of the gallery, for example, on the roof bars then, under the impact of a blast, clouds are formed with a varying ease. Naturally the ease with which clouds are formed depends also on the force of the blast.

The clouds which are being formed within the cross section of a gallery are of varying degrees of concentration; a cloud formed of the dust raised from the roof bars is in a much better position, as regards both its formation and its chance of filling the entire working, than a cloud raised from the floor.

The clouds, in spite of their very strong turbulent motion, do not penetrate each other to a degree sufficient to make the concentration of coal dust and of stone dust uniform in the entire cross section; in other words, to make it correspond to the respective quantities of the two dusts present in the working.

The dust distributed on the floor has a decisive influence on the composition of the dust dispersed near the floor. For the sake of simplicity the dust in question is denominated the floor cloud. Likewise the composition of a cloud formed near the roof is influenced decisively by the dust deposited on the roof bars, air ducts, pipelines situated near the roof and, generally, in the upper part of the gallery. For short, this part of a cloud is called the roof cloud.

The distinctness of the roof and the floor clouds depends also on the height of the working.

Tests were made with the *Barbara* coal dusts *d*25, *d*85 and *d*100. The results obtained are listed in Table 6.4 In this, like in further tables, letters p.w. denote coal dust; p.k. denote stone dust; p.k./p.w. — stone dust on

Table 6.4

Results of Investigations on the Influence of Coal Dust and Stone Dust Being Distributed Separately in the 200 m Gallery upon the Ability of Coal Dust to Propagate Explosions

Dust distribution	Type of dust	Initiator	Minimum incombustible solid matter content sufficient to prevent an explosion:	
			under the conditions of investigations S_B %	in coal dust with stone dust mixtures S %
Roof bars — s.d. Shelves — s.d. Floor — c.d.	*d*85	50 cu m CH_4	85	80
Roof bars — s.d. Shelves — c.d.	*d*85	50 cu m CH_4	90	80
Roof bars — c.d. Shelves — s.d.	*d*85	50 cu m CH_4	95	80
Roof bars — c.d. Floor — s.d./c.d.	*d*85	50 cu m CH_4	90	80
Roof bars — s.d. Shelves — c.d.	*d*85	30mPII	90	87.5
Roof bars — c.d. Shelves — s.d.	*d*85	30mPII	95	87.5
Roof bars — c.d. Floor — s.d.	*d*85	30mPII	97.5	87.5
Roof bars — c.d. Shelves — s.d. Floor — s.d.	*d*85	30mPII	90	87.5
Roof bars — s.d. Shelves — s.d. Floor — c.d.	*d*100	50 cu m CH_4	90	87.5
Roof bars — c.d. Shelves — s.d. Floor — s.d.	*d*100	50 cu m CH_4	95	87.5
Shelves — c.d. Floor — s.d.	*d*100	50 cu m CH_4	95	87.5
Roof bars — s.d. Shelves — s.d. Floor — c.d.	*d*25	50 cu m CH_4	70	72.5
Roof bars — s.d. Shelves — s.d.	*d*25	50 cu m CH_4	80	72.5
Roof bars — c.d. Floor — s.d./c.d.	*d*25	50 cu m CH_4	80	72.5

Note: c.d. — coal dust; s.d. — stone dust; s.d./c.d. — stone dust on coal dust.

coal dust. On the basis of these tests it can be stated that — when coal dust and stone dust are distributed separately — the clouds that are being formed preserve a certain distinctness and do not penetrate each other easily in spite of the energetic turbulent motion in the medium in front of the flame. The cloud called the roof cloud presents a great danger if it is formed through the raising to the air of fine coal dust accumulated in the upper parts of the working.

The enormous activity of a roof cloud in an explosion is illustrated by the following established facts: stone dust placed on the roof bars does not counteract effectively the propagation of a coal dust explosion if on the sidewalls, in the upper part of the gallery, coal dust is present in quantities even seven times smaller than the quantities of stone dust; even 75 g of coal dust per 1 cu cm of the working might, under these conditions, suffice to propagate an explosion.

If in a roof cloud coal dust participates which was raised from roof bars, even a sixteen times greater quantity of stone dust distributed in the gallery might fail to check a coal dust explosion for the propagation of which — under the described conditions — the bare 100 g of coal dust per 1 cu m would suffice.

The medium coal dust, much more frequently found in our mines than the fine dust, presents a smaller danger in a roof cloud than the fine dust.

The floor cloud, in which fine coal dust participates, can be very dangerous even if the total content of incombustible matter in the dust of the working is higher than that required by regulations.

The tests referred to above have shown very distinctly the occurrence of separate clouds of dust in the cross section of the working, contingent upon the distribution, in particular parts of the working, of dusts possessing different properties — that is, of dusts differing as to the degree of their fineness and as to their contents of incombustible solid matter. This fact is of a very considerable importance to the ascertainment of the hazard of coal dust explosions. The practical conclusions drawn from this fact will be presented later on together with the consideration of the prevention of the propagation of coal dust explosions through the dusting of workings with stone dust.

6.2.2. The hazard of explosions in belt-conveyor roads

Belt-conveyor roads, in which very frequently large quantities of dangerous coal dust accumulate, present a particular hazard.

In belt-conveyor roads one finds, as a rule, a strip of the floor covered with dangerous coal dust along the conveyor. The width of this strip is

at least equal to the width of the conveyor. To make safe the coal dust, spread along the conveyor, is a task presenting considerable practical difficulties. To get better acquainted with this problem special investigations [32] were carried out in the *EM Barbara* in the 200 m experimental gallery 2.5 m wide.

The floor of this gallery was spread with the *Barbara* coal dusts *d*85, *d*50, and *d*25, in strips varying in their widths, placed either symmetrically in the middle of the floor or close to the sidewalls of the gallery. These strips were intended to represent the limits of the dangerous coal dust accumulated along the conveyor. The remaining surface of the floor was covered with pure stone dust or with a mixture of stone dust with coal dust. In some of the tests the stone dust, or its mixture with coal dust, had also been distributed on shelves extending along the sidewalls and located on the roof bars. Of course it is impossible in the mining practice to obtain conditions in which pure stone dust could be present outside of the conveyor. In the test in question, however, the intention had been to create extreme conditions.

Explosion initiators used were either 50 cu m CH_4 or 30mPII.

The aim of these tests had been to determine, under given conditions of experiments, the minimum width of a strip of pure coal dust at which the propagation of an explosion occurs, and the maximum width of a strip of pure coal dust at which an explosion is not propagated.

In Table 6.5, in which the results of the above tests are scheduled, the strip of pure coal dust is called, for short, the explosive strip. On the other hand the strips of stone dust, or of a mixture of stone dust and coal dust, are called inexplosive strips. The table includes also the general content of incombustible solid matter n in the entirety of the coal and stone dusts distributed in the gallery, as well as (for comparative purposes) the minimum content of incombustible matter in a uniform mixture of coal dust with stone dust S sufficient to make the propagation of an explosion impossible according to the results of tests obtained in a different series of experiments. The minimum width of the explosive strips, at which the propagation of an explosion occurs, is denoted by the symbol K_p and the maximum width of this strip, at which no propagation of an explosion takes place, is denoted by the symbol K_n. The mixture of coal dust with stone dust is denoted by letters m.d., and the figures given next to these letters refer to the percentage content of incombustible matter in the mixture; figures in brackets, given in the columns marked K_p and K_n, indicate that only a single test has been carried out with the relevant width of the explosive strip.

The results of the tests presented in Table 6.5 may be interpreted as follows:

Table 6.5

Results of Investigations Carried out in the 200 m Gallery on the Width of the "Explosive Strips" of Coal Dust on the Floor

Type of dust	Initiator	n %	S %	Dust distribution					K_p m	K_n m
				floor		non-explosive strip	roof bars	shelves		
				middle explosive strip	sidewall explosive strip					
*d*85	50 cu m CH_4	80.0	80.0	c.d.	—	s.d.	—	—	0.50	0.30
		85.0		c.d.	—	s.d	—	—	0.50	0.40
*d*85	50 cu m CH_4	85.0	80.0	c.d.	—	s.d.	—	s.d.		0.75
*d*85	50 cu m CH_4	85.0	80.0	—	c.d.	s.d.	—	—	0.50	0.40
*d*85	50 cu m CH_4	85.0	80.0	c.d.	—	s.d.	—	m.d. 85.0	(0.75)	
*d*85	30mPII	85.0	87.5	c.d.	—	s.d.	—	—	0.50	0.40
*d*85	30mPII	85.0	87.5	c.d.	—	s.d.	m.d. 85.0	m.d. 85.0	(0.50)	
*d*85	30mPII	85.0	87.5	—	c.d.	s.d.	—	—	0.40	0.30
*d*25	50 cu m CH_4	80.0	60.0	c.d.	—	s.d.	—	—		(1.00)
*d*25	50 cu m CH_4	62.3	60.0	c.d.	—	m.d. 85.0	—	—	(0.75)	
*d*25	50 cu m CH_4	56.4	60.0	c.d.	—	m.d. 80.0	—	—		(1.00)
*d*25	50 cu m CH_4	51.1	60.0	c.d.	—	m.d. 72.5	—	—	(0.75)	
*d*25	30mPII	80.0								
		75.0	75.0	c.d.	—	s.d.	—	—		1.00
		70.0								
*d*25	30mPII	56.4	75.0	c.d.	—	m.d. 80.0	—	—	(1.00)	
*d*25	30mPII	75.0	75.0	—	c.d.	s.d	—	—	(0.75)	0.50
*d*25	30mPII	75.0	75.0	—	c.d.	s.d.	m.d. 75.0	m.d. 75.0	(0.75)	
*d*50	50 cu m CH_4	85.0	not determined	c.d.	—	s.d.	—	—		(0.75)
*d*50	50 cu m CH_4	66.4		c.d.	—	m.d. 80.0	m.d. 80.0	m.d. 80.0		0.75
*d*50	30mPII	80.0		—	c.d.	s.d.	—	—	0.50	0.40
*d*50	30mPII	66.4	not determined	c.d.	—	m.d. 80 0	m.d. 80.0	m.d. 80.0	1.00	0.75
		63.1								

Note: c.d. — coal dust; s.d. — stone dust; m.d. — mixed dust.

— A strip of pure coal dust extending lengthwise on the floor of a gallery constitutes a big danger of a coal dust explosion being propagated because of its presence, in spite of the efforts made to dust the gallery with stone dust according to regulations. A strip of this kind is usually present in belt-conveyor roads.

— The conditions for the propagation of an explosion are easier when the strip of coal dust runs close to the sidewall than in the case of it being located more or less in the middle of the gallery.

— The danger presented by the strip of coal dust on the floor of a gallery increases very noticeably with the rise in the degree of the fineness of the dust.

— The danger presented by the strip of coal dust is obviously the greater the lower is the value of K_p — that is, the smaller is the width of the strip at which the propagation of an explosion of coal dust still occurs.

— For the d85 dust $K_p = 40$ cm (the middle strip); for d85 dust $K_p = 50$ cm (the strip close to the sidewall); for the d25 dust $K_p = 75$ cm (the strip close to the sidewall).

— The fact established through the experiments that relatively narrow strips of coal dust on the floor were able to propagate an explosion proves that they produced sufficiently distinct clouds of dangerous coal dust, within the cross section of the gallery, capable of propagating an explosion in spite of being surrounded by clouds of inexplosive dust.

Practical conclusions derived from the above described tests will be discussed together with the discussion of the methods of supperessing coal dust explosions.

To illustrate the tests in question a diagram is shown in Fig. 6.2 representing the propagation of an explosion through the middle strip of the d85 pure coal dust 0.50 m wide. On both sides of this strip, on the floor of the gallery, pure stone dust was distributed.

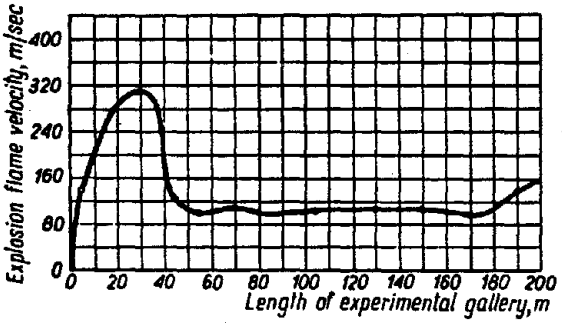


Fig. 6.2. A diagram of explosion No. 3406 (Table 6.5) illustrating the propagation of an explosion through the middle strip of the d85 coal dust in the 200 m gallery; on both sides of the coal dust strip on the floor, pure stone dust; total content of $n = 80\%$; initiator: 50 cu m CH_4 (9.5%).

6.3. THE EFFECT OF THE FIREDAMP CONTENT IN THE AIR OF THE WORKIGS UPON THE EXPLOSIBILITY OF COAL DUST

The presence of methane in the air of the workings has the effect of increasing the explosibility of coal dust which means that — if the air of a working contains methane in quantities causing an increased explosibility of coal dust — it becomes necessary, in order to make this dust incapable of propagating an explosion, to increase the content of incombustible solid matter in the dust. This is the natural consequence of the fact that during an explosion methane participates in the combustion of the explosive medium.

A very simple formula aids in the determination of the percentage by which the content of incombustible solid matter in coal dust ought to be increased if the concentration of methane in the air of the working equals one percent

$$n = \frac{100 - S}{5} \%$$ (6.1)

where S denotes the minimum content of incombustible solid matter strictly sufficient to make the given coal dust unable to propagate an explosion.

If, therefore, the concentration of methane in the air amounted to, for example, x percent the content of incombustible solid matter in the dust would have to be increased by $n \cdot x$ percent.

Of course if a working contains an explosive mixture of methane, then that mixture can explode by itself without the participation of coal dust.

The formula (6.1) is sufficiently accurate for the cases in which the working contains a uniform mixture of methane with the air. When methane accumulations behind the support or roof layers of methane, are present they constitute a special danger discussed already in Section 5.3, since they are able to transmit the flame without the presence of coal dust.

Accumulations of methane in varying concentrations within the cross section of a working cause naturally additional complications in the course of an explosion and can influence more strongly the explosibility of coal dust than a uniform mixture of methane with the air of the working.

6.4. EFFECTS OF THE CHARACTERISTICS OF THE WORKINGS UPON THE COURSE OF COAL DUST EXPLOSIONS

6.4.1. The effect of the length of zones containing dangerous coal dust upon the course of explosions

In mines the length of workings containing dangerous coal dust varies very considerably. This factor influences enormously the course of explosions and their effects. Short sections of workings, containing dangerous deposits of coal dust, are in danger of going through a local, not fully developed, explosion. According to Polish regulations this corresponds to zones not exceeding 30 m in length. In the measure in which the length of the workings containing dangerous coal dust increases, the scope of the possible disaster becomes greater; in other words: the longer the way over which the flame passes the higher the scope of disaster. Note, however, that the number of victims of a disaster does not depend upon its scope but upon the disposition of men in the zone affected by the disaster.

When many workers happen to be present within the reach of an explosion of a relatively limited scope such an explosion might cause very heavy losses in human lives. The reverse is likewise possible: an explosion of a great dimension can cause relatively few casualties. But these are matters of chance. On the whole it ought to be assumed that the longer are the zones containing dangerous coal dust, especially when they begin at the advancing face of a working, or at places of the possible accumulation of methane, the greater is the hazard. The zones containing dangerous coal dust, which reach a shaft, present the greatest hazard. An explosion reaching a shaft can very easily destroy the installations and equipment of the shaft and this, depending on the type of the shaft, may cause a particularly great disaster the effects of which will be felt even on the surface.

There are many factors upon which depends the length of zones containing dangerous coal dust. It would serve no purpose to enumerate all these factors the more so since they are well known in the coal industry. Yet one ought to point out the great role played by workings in which belt-conveyors are operated. In belt-conveyor roads, in a majority of cases, dangerous coal dust is present. Considering the length of zones, containing dangerous coal dust, it ought to be remembered that the question concerns the length of zones over which an explosion of coal dust can develop without any interruption. In Polish coal mines, according to general data in the possession of the *EM Barbara*, the maximum lengths of zones containing dangerous coal dust approach 2 km. Naturally this is not the highest

limit. In the great mine disasters the flame of a coal dust explosion had been known to travel over much longer distances.

Speaking of zones containing dangerous coal dust one should not forget that the flame of an explosion, as a rule, travels much farther than the length of the zone since the blast carries the dust over much bigger distances; in particular when dust accumulations are of an appreciable size the explosive medium may extend over a length of workings several times the length of the zones containing dangerous coal dust.

The length of the zone of dangerous coal dust exerts also a decisive influence on the so-called steady propagation of a coal dust explosion. This phenomenon, on account of its great importance, has to be discussed separately.

Because of the length of mine roads containing dangerous coal dust it becomes necessary to carry out tests of coal dust explosions in the longest possible experimental galleries.

The length of 400 m for an experimental gallery may be regarded as adequate, but the very important thing is to see that the length of the zone to be examined in the gallery should not be materially shortened through the influence of the rarefaction wave (Section 2.3.3.2). On this account the underground experimental galleries are much more useful than the surface experimental galleries. Indeed for the investigation of problems connected with coal dust explosions, and of methods of preventing the hazard of such explosions, it is greatly desirable to have experimental galleries developed much more than they are now as regards both their cross section areas and the total length of the system of such galleries.

6.4.2. The effect of the magnitude of the lateral cross sections of the workings and of the network system of the workings upon the course of explosions

The cross section areas, as well as the bends and ramifications of workings, exert a great influence on the initiation and development of coal dust explosions. It is also a matter of general knowledge that mine workings represent a great variety of types and systems.

To make a study of the influence, exerted by this tremendous variety of workings, upon the courses of coal dust explosions is practically impossible. The task of this kind would have required a great number of experimental galleries which, moreover, would have to be provided with the necessary instruments. Besides, such investigations would have been very expensive and labor consuming. Now and again an opportunity offers to carry out a limited number of experiments in mines excluded from exploitation as witness the investigations on barriers carried out in the

Federal Republic of Germany. But systematic investigations under reproducible conditions are not possible in such circumstances. Therefore, the greatest number of basic investigations was carried out in rectilinear level underground experimental galleries and in surface experimental galleries. Some research work has been done also in parallel galleries connected by crosscuts in the *EM Bruceton* in the USA.

The course of explosions is influenced by the cross section of workings, as well as by their surface and the type of support. The various shapes of the cross sections of experimental galleries were given in Fig. 2.24 after a British investigator [136].

An already developed explosion of coal dust propagates itself with more ease in a working of a larger cross section area than it does in a working of a smaller cross section area within the range of dimensions of workings one can find in mines. This means that the same coal dust must contain somewhat more incombustible solid matter if it is to become incapable of propagating an explosion in a working of a large cross section area. A certain difference has been observed, for instance, in the course of comparative tests carried out in the *EM Barbara* in the galleries the cross section areas of which measured 5 and 7.5 sq m, respectively.

Yet it must be admitted that an explosion of coal dust can be initiated more easily — that is, by a weaker initiator in a working of smaller cross section area. This is so because the formation of a primary cloud, filling the entire cross section of a working, is the more easy the smaller is the cross section area of the working. For this reason explosions are most easily initiated in roadways. The initiation of an explosion, where shortwall or longwall exploitation of coal is in progress, is more difficult though the explosion most disastrous in its effects in the *Honkeiko* mine in Manchuria (1527 victims) was initiated by the explosion of methane in a longwall.

It has been noticed since long ago that the rough walls of a roadway and the presence of support facilitate the development of a coal dust explosion; this is explained by the fact that under such conditions the turbulence becomes more intensive. The influence of conditions prevailing in particular experimental underground galleries finds its expression in the differences between the values of S found in different galleries. Ramsay shows a very interesting diagram (Fig. 6.3) which can give a good idea of the extent of these differences. The diagram in question marks the different quantities of incombustible solid matter per weight unit of coal dust which are required to make coal dust unable to propagate explosions in different experimental galleries.

It is worth mentioning that, so far, no investigations on the explosibility of coal dust were carried out in inclined or rising workings.

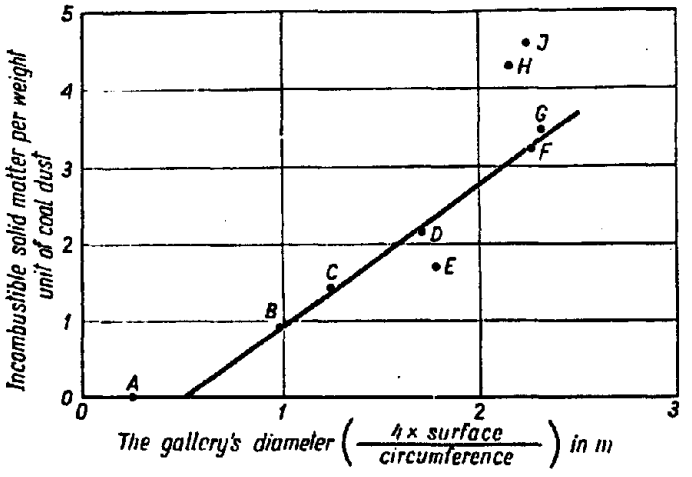


Fig. 6.3. The quantity of incombustible solid matter per weight unit of coal dust necessary for the prevention of the propagation of explosions in various experimental galleries; the content of volatile matter in coal dust ~ 36% [136]: *A* — Allison (1926); *B* — Mason and Wheeler (1927); *C* — Mason and Wheeler (1933); *D* — Audibert and Delmas (1931); *E* — Wilke (1937); *F* — Committee for the Investigation of Explosions in Mines (1913); *G* — Rice et al. (1922); *H* — Taffanel (1921); *J* — Cybulski (1952); *A–F* — smooth steel experimental galleries; *G–J* — experimental galleries in mines.

6.4.3. The effect of connected galleries upon the explosibility of coal dust

All the above described basic investigations were carried out in blind, rectilinear experimental galleries. Such conditions are not found frequently in mines. For the development of a coal dust explosion these conditions are the most simple and the results obtained justify the assumption that the development of explosions is the easiest under such conditions.

Therefore, the results obtained in the tests in question serve as premises for the formulation of practical conclusions according to the principle requiring that the most dangerous, among the possible, conditions must be taken into account when appropriate safety measures are being determined.

Working in mines are — more frequently than not — connected with each other a fact which complicates the course of an explosion. It may hamper but — in some cases — it may also facilitate the development of an explosion. Of foreign investigations on the subject the only one known to the present author is the British work [82] carried out in an underground gallery 228 m long, measuring 228 cm in diameter.

The authors of the work cited made use of partly open slits in the surface gallery behind the point at which coal dust explosions were in-

itiated. Actually no comparative tests were made concerning the explosibility of coal dust under these changed conditions. It has been established only that the opening of the gallery, behind the point at which explosions were initiated, caused a lowering of the velocity of the flame and of the pressure.

On the other hand slits in the gallery ahead of the point at which explosions were initiated caused, at first, an acceleration of the velocity of the flame but then, after the front of the flame had passed the opening in the gallery, the velocity of the flame declined. These results were logically quite justified.

A slit in the "face" of a surface experimental gallery naturally lowers the pressure of the coal dust cloud undergoing the process of combustion, and this lowers the velocity of the flame. A slit ahead of the flame causes the formation of a rarefaction wave which, when it reaches the front of the flame, causes its acceleration. But a slit behind the front of the flame lowers the pressure and automatically lowers the velocity of the flame. Entirely analogous phenomena occur in mine workings.

In the *EM Barbara* investigations were carried out with high accuracy on the effects of the connection between the 200 m and the 400 m gallery upon the explosibility of the *d*85 and *d*25 coal dusts [48]. The explosibility was determined of the coal dust in the 200 m gallery connected with the 400 m gallery and, the other way round, the explosibility of the coal dust in the 400 m gallery connected with the 200 m gallery. A sufficient number of experimental data was obtained to make a statistical analysis possible. In both instances as a result of the lowering of the pressure in the gallery behind the front of the flame, through the possibility given to the combustion products to expand into the connecting and into the other gallery, the content of incombustible solid matter, necessary to safeguard against the propagation of an explosion, has been lower than in the case of a single gallery.

In the 200 m experimental gallery, with the probability of the propagation of an explosion $P = 0.5$, the relevant differences in the value of n, denoted by the symbol Δ_{200}, amounted to 5 percent for the *d*85 coal dust and to 8.7 percent for the *d*25 coal dust.

In the 400 m experimental gallery with the probability of the propagation of an explosion $P = 0.5$ the difference for the *d*85 dust amounted to 4.5 percent. This value increases with the decrease of the probability; for example, with the $P = 10^{-3}$ the difference amounts to 5.9 percent.

It must be stated that, if the connections between the galleries had larger cross section areas, the influence exerted by these connections would have been greater than that found in the above tests. Likewise if the initiators had been weaker than those used in the tests the influence

exerted by connections situated in the vicinity of the face of the gallery, by way of hampering the development of an explosion, would have been greater than that observed in the tests described here.

The velocities of the flame, compared for the same values of n, were slightly higher in the case of connected galleries than in the case of blind galleries. It is interesting to make a comparison between the course of the explosion of the *d*85 *Barbara* dust with $n = 67.5$ percent and with the initiator 30mPII in a blind 400 m gallery, and the explosion of the same dust with the same explosion initiator in a 400 m gallery connected by a connecting gallery with the 200 m gallery. The courses taken by the two explosions are shown in Fig. 6.4.

In the case of both experiments were calculated, with the aid of an electronic computer, regression equations representing the distance traveled by the flame — in relation to time — throughout the entire 400 m gallery. On the basis of these equations were next determined: the mean velocities of the flame for the entire length of the gallery v_{sr}, the velocities of the flame at the end of the gallery v_{400}, and the acceleration (retardation) a.

For the explosion No. 26 (Fig. 6.4*a*) the regression equation was determined in the following form

$$x = -62.97 + 171.89t - 11.76t^2 \tag{6.2}$$

$v_{sr} = 123.4$ m/sec $\qquad a = -23.6$ m/sec^2

$v_{400} = 88$ m/sec

For the explosion No. 693 (Fig. 6.4*b*) the regression equation takes the following form

$$x = 23.36 + 86.55t - 0.72t^2 \tag{6.3}$$

$v_{sr} = 83.6$ m/sec $\qquad a = -1.2$ m/sec^2

$v_{400} = 81$ m/sec

It must be stated that a comparison made between merely two experiments may serve only as an example. In the diagram shown in Fig. 6.4*b* of considerable interest is the development of the flame in the connecting gallery which, as in all analogous experiments in the series of investigations discussed here, had not been covered with coal dust.

The explosions initiated at the face of the 400 m gallery developed also in the connecting gallery because the blast wave, formed through the combustion of the primary cloud in the zone of the initiation, carried also a cloud of coal dust to the connecting gallery. Though the conditions of the experiment were such that the branching off from the experimental gallery had been situated in the close vicinity of the face of this gallery yet, because of the strength of the explosion initiator and of the initial absence of coal dust in the connecting gallery, the front of the flame

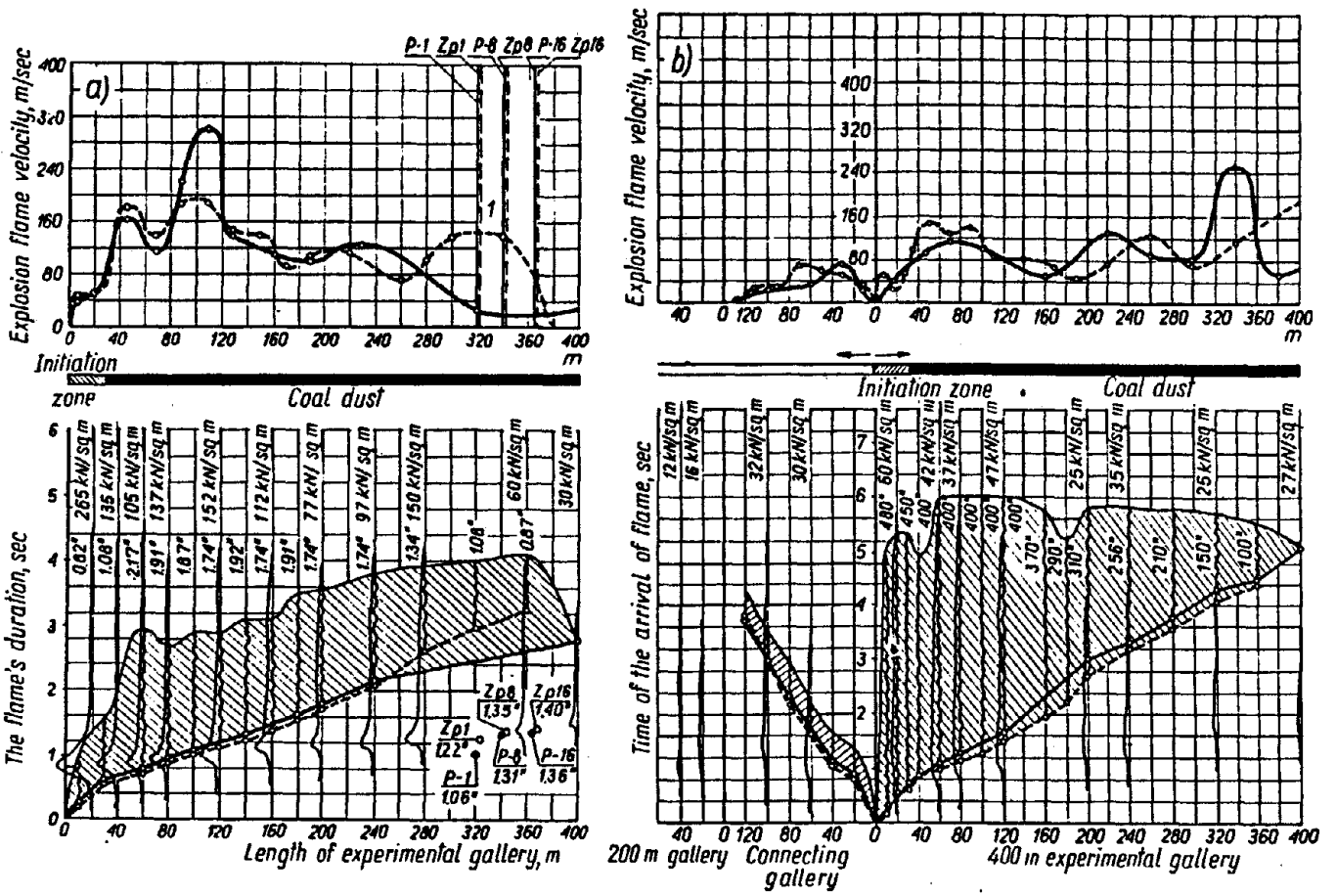


Fig. 6.4. Diagrams of explosions of the d85 *Barbara* coal dust: *a* — explosion No. 26; $n = 67.5\%$, initiator 30mPII, 400 m gallery, easiest dispersion conditions; *1* — barrier of 16 shelves, 1875 kg of stone dust, $Q = 250$ kg/sq m; *b* — explosion No. 693: $n = 67.5\%$, initiator 30mPII, 400 m gallery connected with 200 m gallery, easiest dispersion conditions. Explanation of symbols: *P-1* means first shelf; analogically — *P-8*, *P-16*, etc; *Zp1* means wire net of the first shelf; analogically *Zp8*, *Zp16*, etc; numbers written below these symbols, e.g., 1.35″, 1.40″, etc. mean the time of putting a given shelf into action t_p.

progressed in the 400 m experimental gallery at a higher velocity than it did in the connecting gallery. In consequence, after the fading away of the flame in the connecting gallery, this gallery continued to exert its influence of a typical nature upon the further course of the flame in the 400 m experimental gallery.

Very essential is also the comparison between the mean velocities and the accelerations in the two experiments.

Though the actual conditions in mine workings are very complicated yet the experiments which were carried out show that, in circumstances similar to those in which these experiments were made, the regulation requirements provide a certain additional margin of security.

6.5. BASIC INVESTIGATIONS ON THE STEADY PROPAGATION OF A COAL DUST EXPLOSION

6.5.1. The absolute explosibility of coal dust determined under conditions of a steady propagation of an explosion

In the foregoing chapters the influence was discussed which the explosion initiator, the dimensions and the system of the network of workings exert upon the explosibility of coal dust. In the determination of the explosibility of coal dust — especially when a very strong initiator is used — a great role is played by the length of the zone on which tests are carried out. The direct influence of very strong initiators on the explosibility of coal dust is the greater the shorter the zone over which the examinations are made, since the influence of a very strong initiator can extend over a distance exceeding 100 m.

In order to determine the real explosibility of coal dust, which could also be called the absolute explosibility, tests should be made with the use of a very strong initiator — that is, so strong as to be capable of being classified as practically of the maximum strength occurring in the mining practice. Besides, the tests should be made beyond the zone of the direct influence of the initiator — that is, under conditions in which the development of a coal dust explosion is already left to itself. The explosibility of coal dust determined under such conditions can be regarded as absolute. In accordance with the above explanations the absolute explosibility of coal dust is the one determined under the conditions of steady propagation of an explosion.

6.5.2. Investigations on the absolute explosibility of coal dust

The special basic investigations on the absolute explosibility of coal dust were carried out in the *EM Barbara* in the 200 m gallery the cross

section area of which measured 5 sq m, and in the 400 m gallery the cross section of which was 7.5 sq m.

Coal dust from the *Barbara* seam and the initiator 30mPII were used in these tests.

Separate series of tests were carried out for the *d*25 and *d*85 dusts in the 200 m as well as in the 400 m galleries in order to obtain accurate comparative results. However only the tests made in the 400 m gallery, as could be concluded from the totality of investigations conducted over a period of many years, supplied the data necessary for determining the explosibility of coal dust under conditions of the steady propagation of its explosion.

For the purpose of collecting experimental material, sufficiently extensive to be analyzed statistically, tests were made in both galleries with the contents of incombustible solid matter n in the dust varying by a regular interval of 2.5 percent each time. The frequency with which the propagation of the explosions occurred was noted.

The details of statistical computations are given in the publication [44].

Table 6.6

Results of Investigations on the Degree of Explosibility S of the *d*85 Dust in the 200 m Experimental Gallery with the Use of the 30mPII Initiator

Incombustible solid matter content n %	Frequency of the propagation of explosions p	Eqaulized probabilities of the propagation of explosions P	Limits of the confidence intervals for P: lower limit P_d	Limits of the confidence intervals for P: upper limit P_g
75	1.000	0.940	0.830	0.984
77.5	0.910	0.801	0.679	0.890
80	0.511	0.554	0.459	0.646
82.5	0.250	0.283	0.188	0.396
85	0.156	0.100	0.036	0.220
87.5	0.000	0.023	0.003	0.106
90	—	$3.5 \cdot 10^{-3}$	$1.1 \cdot 10^{-4}$	$4.3 \cdot 10^{-2}$
92.5	—	$3.3 \cdot 10^{-4}$	0	$1.5 \cdot 10^{-3}$
95	—	$2 \cdot 10^{-3}$	0	$4.1 \cdot 10^{-3}$

Note: values for n = 90.0, 92.5 and 95% are extrapolated.

The summary of the results of the investigations on the degree of the explosibility S in the 200 m gallery for both coal dusts is given in Tables 6.6 and 6.7, and the results of the investigations on the degree of the explosibility S_u — that is, under the conditions of the steady propaga-

Table 6.7

Results of Investigations on the Degree of Explosibility S of the $d25$ Dust in the 200 m Experimental Gallery with the Use of the 30mPII Initiator

Incombustible solid matter content n, %	Frequency of the propagation of explosions p	Equalized probabilities of the propagation of explosions P	Limits of the confidence intervals for P: lower limit P_d	upper limit P_g
65	0.700	0.760	0.595	0.879
67.5	0.500	0.538	0.413	0.660
70	0.417	0.304	0.181	0.456
72.5	0.091	0.132	0.039	0.313
75	0.000	0.042	0.004	0.204
77.5	—	10^{-2}	$2.2 \cdot 10^{-4}$	$12.5 \cdot 10^{-2}$
80	—	$1.7 \cdot 10^{-3}$	$5 \cdot 10^{-6}$	$71 \cdot 10^{-3}$
82.5	—	$2 \cdot 10^{-4}$	0	$37 \cdot 10^{-2}$

Note: values for n = 77.5, 80.0 and 82.5% are extrapolated.

Table 6.8

Results of Investigations on the Degree of Explosibility S_u of the $d85$ Dust in the 400 m Experimental Gallery with the Use of the 30mPII Initiator

Incombustible solid matter content n, %	Frequency of the propagation of explosions p	Equalized probabilities of the propagation of explosions P	Limits of the confidence intervals for P: lower limit P_d	upper limit P_g
67.5	1.00	0.984	0.783	0.9997
70	0.83	0.887	0.613	0.983
72.5	0.60	0.610	0.358	0.821
75	0.40	0.257	0.083	0.532
77.5	0.00	0.056	0.003	0.316
80	0.00	0.006	0	0.172
82.5	—	$3 \cdot 10^{-4}$	0	$8.4 \cdot 10^{-2}$
85	—	$3 \cdot 10^{-6}$	0	$3.6 \cdot 10^{-2}$

Note: values for n = 80.0, 82.5 and 85.0% are extrapolated.

tion of explosions in the 400 m gallery are presented in Tables 6.8 and 6.9. Summaries of these results are contained in Tables 6.6–6.9; apart from that, very important and essential information, concerning the degree of the explosibility S and S_u of the $d85$ and the $d25$ dusts for specified four magnitudes of probability, is given in Table 6.10.

The values n_d and n_g in Table 6.10 denote the estimated limits of the

confidence intervals at the level of confidence $x = 0.05$ which means that the probability of these limits being transgressed equals 5 percent.

The values of S_u given in Table 6.10 for the 400 m gallery refer to the steady propagation of an explosion and may be regarded as absolute magnitudes because, as has been explained previously, the tests were carried out with the use of a very strong initiator and the values of S_u were determined in a zone beyond the direct influence of the initiator.

Table 6.9

Results of Investigations on the Degree of Explosibility S_u of the *d*25 Dust in the 400 m Experimental Gallery with the Use of the 30mPII Initiator

Incombustible solid matter content n, %	Frequency of the propagation of explosions p	Equalized probabilities of the propagation of explosions P	Limits of the confidence intervals for P: lower limit P_d	upper limit P_g
55	0.9	0.873	0.625	0.975
57.5	0.5	0.625	0.404	0.811
60	0.4	0.307	0.143	0.524
62.5	0.1	0.093	0.016	0.308
65	0.0	0.016	0.00043	0.168
67.5	—	0.0015	0	0.083
70	—	0.000075	0	0.035
72.5	—	—	0	0.013

Worthy of attention in Table 6.10 is the mean value given there of the normal scatter m — that is, the value of the content of incombustible solid matter at which, under given conditions, the probability of the propagation of an explosion amounts to 50 percent. These are very characteristic values.

Table 6.10 ought to be regarded as comprising data of a fundamental importance in the formulation of instructions containing requirements as to the contents of incombustible solid matter in the mine dust. With the aid of this table it is possible to estimate the probable measure of safety offered by a given requirement on the assumption that it ought to prevent the propagation of an explosion over a zone of 200 or 400 m.

The values of S_u, determined for the zone of 400 m, indicate that — when the pertinent probability is maintained — below these values the propagation of a coal dust explosion is possible over unlimited distances — that is, that below these values a steady propagation of a coal dust explosion can already take place.

Many conclusions derive from the data included in Tables from 6.6

Table 6.10

A Summary of the Results of Investigations on the Degrees of Explosibility S and S_u of the $d85$ and $d25$ Dusts from the *Barbara* Seam Carried out in the 200 and 400 m Experimental Galleries with the Use of the 30mPII Initiator. The Data Is Computed for Four Values of Probability

Type of coal dust	Experimental gallery m	Probability of the propagation of the explosions P	Incombustible solid matter content S in 200 m gallery: S_u in 400 m gallery %	Mean value of the normal distribution m	Limits of the confidence intervals n for P: lower limit n_d	Limits of the confidence intervals n for P: upper limit n_g	Standard deviations of the normal distribution s
$d85$	200	10^{-2}	88.7		85.7	91.7	
$d85$	200	10^{-3}	91.4		87.4	95.3	
$d85$	200	10^{-4}	93.6		88.9	98.3	
$d85$	200	$5 \cdot 10^{-1}$		80.5	79.6	81.4	3.52 ± 0.62
$d85$	400	10^{-2}	79.5		75.5	83.4	
$d85$	400	10^{-3}	81.5		76.5	86.6	
$d85$	400	10^{-4}	83.2		77.3	89.2	
$d85$	400	$5 \cdot 10^{-1}$		73.2	71.5	74.9	2.68 ± 0.76
$d25$	200	10^{-2}	77.5		72.6	82.3	
$d25$	200	10^{-3}	80.6		74.3	87.0	
$d25$	200	10^{-4}	83.2		75.6	90.7	
$d25$	200	$5 \cdot 10^{-1}$		67.9	66.4	69.4	4.10 ± 1.01
$d25$	400	10^{-2}	65.5		63.6	67.5	
$d25$	400	10^{-3}	67.9		65.4	70.3	
$d25$	400	10^{-4}	69.8		66.8	72.7	
$d25$	400	$5 \cdot 10^{-1}$		58.5	56.9	60.1	3.04 ± 0.78

to 6.10 particularly, however, in Table 6.10. The most important of them are cited in Section 6.5.3.

6.5.3. Conclusions from the examination of the steady propagation of a coal dust explosion

In order to make the dust incapable of propagating an explosion, when the same probability is assumed, considerably higher values of S are required in the 200 m gallery than the values of S_u in a 400 m gallery. For example, when the adopted probability $P = 10^{-2}$ the value of S for the $d85$ dust in the 200 m gallery amounts to 88.7 percent, while the value of S_u for the same dust and with the same degree of probability in the 400 m gallery amounts to 79.5 percent.

Thus to make the dust capable of preventing the range of the flame from exceeding 200 m the dust must contain a very large quantity of incombustible solid matter.

Naturally when a lower degree of probability is adopted, e.g., $P = 10^{-3}$, the value of S for the $d85$ dust in a 200 m zone is much higher again and amounts to 91.4 percent, while for the same dust and the same degree of probability in the 400 m gallery the value of S_u amounts to 81.5 percent.

For the $d25$ dust the values of S and S_u, with equal probabilities of an explosion being propagated, are much lower but they are still much higher than those required by regulations; for example: in the 200 m gallery, with the adopted degree of probability $P = 10^{-2}$, the value of S amounts to 77.5 percent and the value of S_u, in the 400 m gallery and with the same degree of probability, amounts to 65.5 percent.

A fact worthy of particular attention is that a relatively slight lowering of the content of incombustible solid matter causes quite a considerable increase of the degree of probability of the propagation of an explosion. For instance, for the $d85$ dust in the 400 m gallery the value of $S = 79.5$ percent corresponds to the degree of probability of the propagation of an explosion equal to 10^{-2} but, when the content of incombustible solid matter in this dust is brought down to 73.2 percent, the degree of probability of an explosion being propagated goes up to $5 \cdot 10^{-1}$ which means that in every other experiment the propagation will take place.

Though to protect mine roads against steady propagation of an explosion over a zone of 400 m much lower contents of incombustible solid matter in the dust are required than in the case of an identical protection, when the zone to be protected is 200 m long, it should be remembered, nevertheless, that an explosion of coal dust propagated over a distance

approaching 200 m is, practically, a great disaster in itself capable of causing a great number of casualties if the miners are present within the range of the explosion, or in mine roads through which the air flows with a high content of CO.

An explosion, whose range of the flame approaches 400 m, threatens to become an even more serious disaster. Therefore, the conclusion suggests itself that, in determining the requirements with regard to the necessary contents of incombustible solid matter in the dangerous coal dust (that is, in the dust containing more than 12 percent of volatile matter), the values of S ought to be taken into consideration which make the dust incapable of propagating an explosion over a distance of 200 m. Unfortunately the relevant values of S, especially for the $d85$ dust, are very high as can be seen in Table 6.10 and as can be concluded from the examples cited in the text. These values are high, of course, if an adequate probability is sought of being actually protected against the propagation of explosions.

In the light of the results of tests included in Table 6.10 regulation requirements appear to be particularly inadequate. To substantiate this, it should be sufficient to state that, in the case of the $d85$ dust containing 75 percent of incombustible solid matter, the propagation of an explosion over a 200 m zone occurred every time when the tests were made. In the 400 m gallery the $d85$ dust, containing the same proportion of incombustible solid matter, propagates an explosion over the entire 400 m zone with a probability degree only slightly below 52 percent (the above values are not included in Table 6.10).

The fact that the cross sectional area of the 200 m gallery measures 5 sq m and that this area in the 400 m gallery measures 7.5 sq m does not affect the validity of the conclusions drawn from the results of the tests concerning the protection of coal dust against the propagation of explosions over a zone of 200 and of 400 m. For, in separate investigations, it was established that the propagation of an explosion over a 200 m zone in the 400 m gallery is easier than in the 200 m gallery. Therefore in order to prevent the propagation of an explosion over a 200 m zone in a gallery the cross sectional area of which is 7.5 sq m even slightly higher values of S are required than those determined in the 200 m gallery.

We shall come back to the conclusions drawn from the results of investigations included in Tables 6.6–6.10 when the means of preventing the danger of coal dust explosions will be discussed particularly when the regulation requirements will be considered.

In order to get the proper idea of the ease with which an explosion can be propagated, in spite of high content of incombustible solid matter in the dust, it is sufficient to examine the mean values of the normal

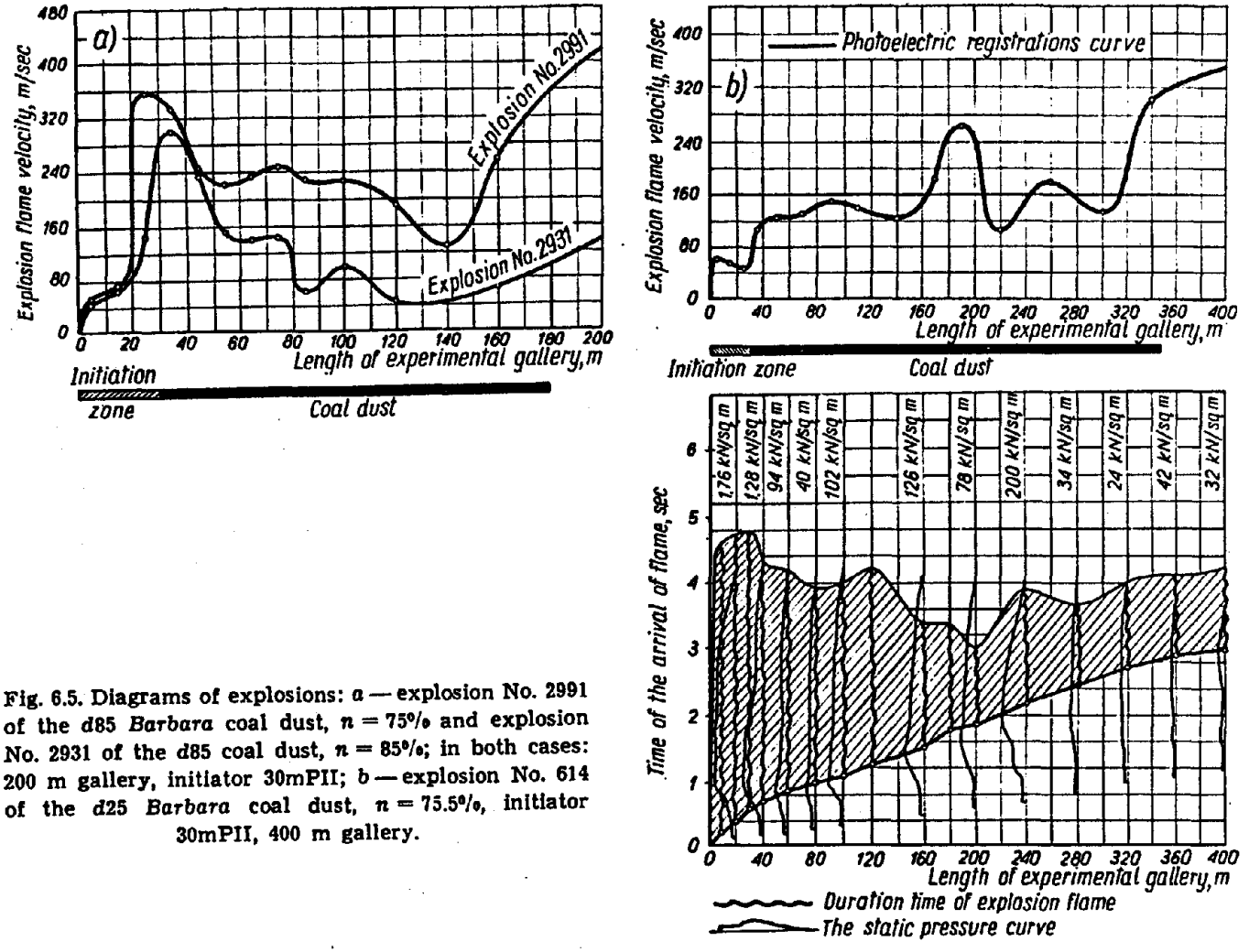


Fig. 6.5. Diagrams of explosions: a — explosion No. 2991 of the d85 *Barbara* coal dust, $n = 75\%$ and explosion No. 2931 of the d85 coal dust, $n = 85\%$; in both cases: 200 m gallery, initiator 30mPII; b — explosion No. 614 of the d25 *Barbara* coal dust, $n = 75.5\%$, initiator 30mPII, 400 m gallery.

scatter of m (Table 6.10) — that is, of the contents of incombustible matter in the $d85$ or in the $d25$ dust with which the degree of probability of the propagation of an explosion equals 0.5.

As an illustration of the results of experiments discussed here very many graphs could be presented showing the course of explosions. In order to economize the space only three examples are given. In Fig. 6.5*a* two graphs are shown one of which represents explosion No. 2991 of the $d85$ coal dust containing $n = 75$ percent, and the other — explosion No. 2931 of the same coal dust in which, however, the content $n = 85$ percent; both explosions taking place in the 200 m gallery. The difference between the courses of the two explosions is visible but the course of the explosion of coal dust, containing 85 percent of incombustible solid matter, is of an essential importance on account of the fact that this explosion passes so assuredly the 200 m zone in spite of such a high value of n. In Fig. 6.5*b* a graph is shown representing an explosion of the $d25$ coal dust, containing 75.5 percent of incombustible solid matter, in the 400 m gallery. As can be seen in this case also the propagation of the dust explosion over a zone of 400 m proceeds quite assuredly. It ought to be stressed that the coal dust used in the last mentioned explosion was of the $d25$ type unlike the fine dust the explosions of which are shown in Fig. 6.5*a*. The coarser dust, in spite of the high value of its content of incombustible solid matter, produced also a sure propagation of the explosion.

6.6 THE EFFECT OF THE DEVELOPMENT OF A COAL DUST EXPLOSION IN TWO DIRECTIONS UPON THE EXPLOSIBILITY OF COAL DUST

6.6.1. The necessity of investigating the problem

Practically all of the basic investigations in the *EM Barbara*, as well as in other (foreign) scientific research institutes were carried out in blind galleries usually rectilinear ones.

Coal dust explosions developed, as a rule, in one direction only.

Under conditions existing in mines, in the majority of cases, explosions develop simultaneously in various directions. Thus the necessity arose of undertaking investigations in circumstances in which explosions of coal dust developed at least in two directions. Naturally these investigations had to be conducted within the limits of the available conditions of experimenting. These conditions are shown in Fig. 2.1 representing the experimental galleries in the *EM Barbara*.

The total length of the two experimental galleries and of the connecting gallery amounts to 740 m. With the rise galleries reaching the surface the entire length of the workings in question is 880 m.

6.6.2. The aim and conditions of the investigations

The aim of the investigations has been to determine the contents of incombustible solid matter S which make fine and medium coal dust unable to propagate explosions in both the 200 m and the 400 m galleries. The values of S so determined had to be compared with the values of S determined in the course of the basic investigations in which coal dust explosions developed in one direction only.

Coal dust explosions were now initiated in the middle of the connecting gallery. These explosions developed in two directions: from the connecting gallery they passed simultaneously to the 400 and to the 200 m galleries. In both of the last mentioned galleries explosions moved in the direction of the outlets.

In these experiments the *d*85 and *d*25 *Barbara* dusts were used. A description of the experiments in question is given in the documentation of the *EM Barbara* for the year 1969 and in the publications [58], [60].

6.6.3. The results of the investigations

In general the course of the explosions — even with the contents of incombustible solid matter only slightly lower than the values of S — was very violent, the flame velocity reaching as much as 1000 m/sec.

In Fig. 6.6*a* a graph is shown, by way of an example, representing the explosion No. 900 of the *d*85 dust. The *d*85 dust in the 200 m gallery contained $n = 82.5$ percent and the same type of dust in the 400 m gallery contained $n = 75$ percent. The propagation of explosions took place in both these galleries. The lower part of the diagram indicates that the flame reached the end of the 200 m gallery in a shorter time than it covered the distance of 200 m in the 400 m gallery exactly as could be expected.

In Fig. 6.6*b* a diagram is shown representing, by way of an example, the explosion No. 908 of the *d*25 dust. The *d*25 dust in the 200 m gallery contained $n = 67.5$ percent, while in the 400 m gallery it contained $n = 50$ percent.

As can be seen in the lower part of the diagram the flame reached the ends of the 200 m and the 400 m galleries, respectively, in approximately the same period of time owing to the higher velocity of the flame in the 400 m gallery.

The contents of incombustible solid matter in the dust sufficient to give protection against the propagation of an explosion, under conditions in which the explosion can develop in two directions, was denoted by the symbol S_{uz} while the corresponding contents under conditions permitting

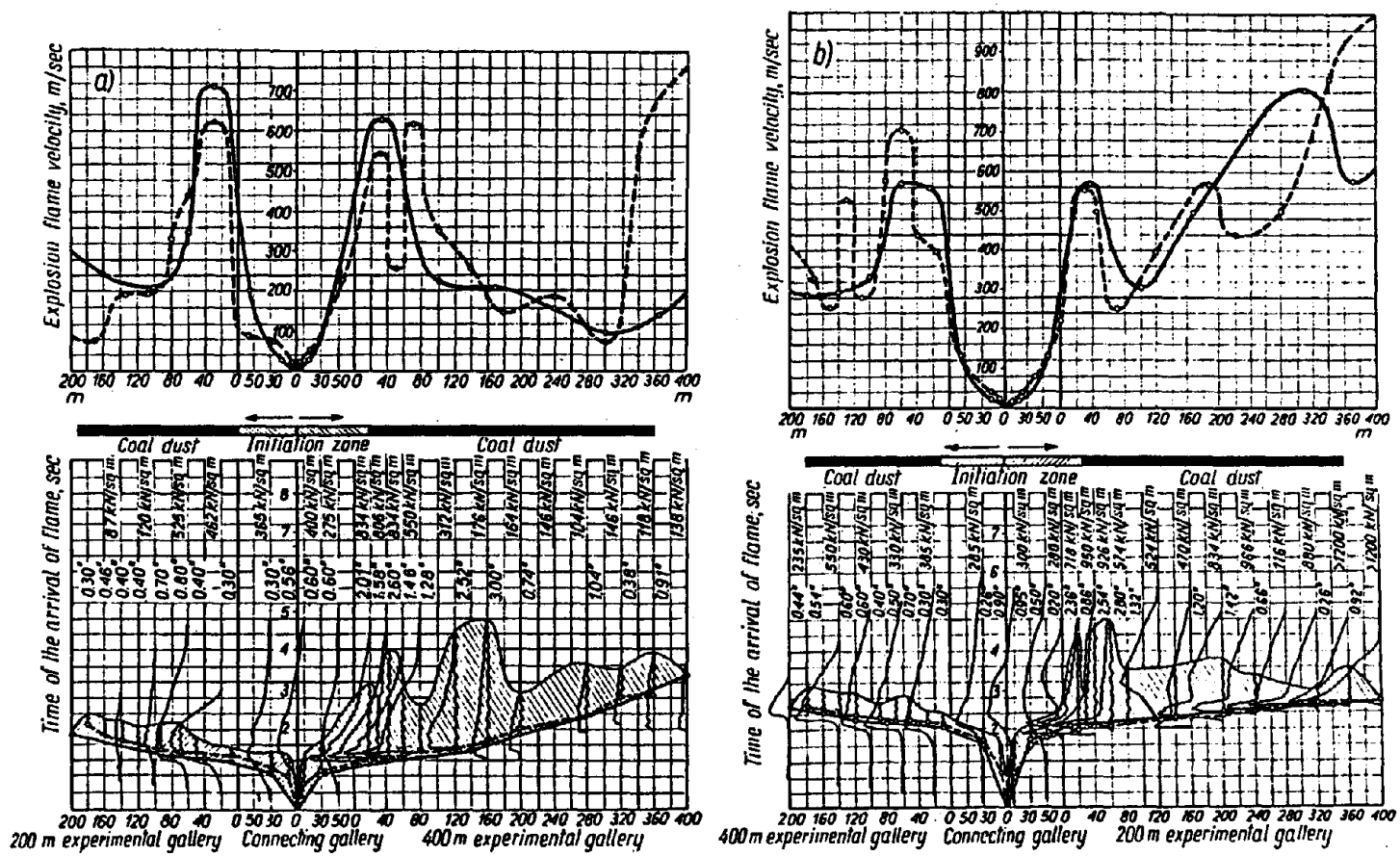


Fig. 6.6. Diagrams of two-directional explosions: a — explosion No. 900 of the *d*85 *Barbara* coal dust, $n = 82.5\%$ in the 200 m gallery, and $n = 75\%$ in the 400 m gallery; b — explosion No. 908 of the *d*25 *Barbara* coal dust, $n = 67.5\%$ in the 200 m gallery and $n = 50\%$ in the 400 m gallery.

a development in one direction only — that is, in a blind gallery, by the symbol S'. The results of the tests are scheduled in Table 6.11. As can be seen by comparing the values of S_{uz} and of S' for the $d85$ and $d25$ dusts, under the conditions of a two-directional development, approximately the same contents of incombustible solid matter are required in order to prevent the propagation of an explosion as in the case of a development in one direction only.

Table 6.11

A Summary of the Results of Investigations on the Explosibility of the $d85$ and $d25$ Coal Dusts in the Two-Directional and Unidirectional Development of the Explosion

Coal dust	Development of explosion:	
	two-directional S_{uz}, %	unidirectional S', %
$d85$		
200 m gallery	87.5	87.5
400 m gallery	77.5	77.5
$d25$		
200 m gallery	77.5	75.0
400 m gallery	65.0	65.0

The values of S_{uz} and of S' given in Table 6.11 refer to the contents of incombustible solid matter as determined directly through the tests. Of course the values of S given in Table 6.10, in which various degrees of probability were taken into consideration, are higher.

In the determination of the values of S_{uz} the number of experiments made was too small for a statistical computation.

6.7. THE PASSING OF A COAL DUST EXPLOSION THROUGH BENDS OF GALLERIES

6.7.1. General information

The basic investigations on the explosibility of coal dust were usually carried out in horizontal and rectilinear underground or surface experimental galleries. In mines, networks of workings are very complicated and, at that, on the way of the development of a possible coal dust explosion one usually meets bends of the workings.

The influence of the system of workings on the course of a coal dust explosion has been discussed already in Section 6.4. Taking into account

the fact that bends of workings are one of the most common characteristics of the roads over which explosions in mines develop, and considering also the influence such bends exert on the application of the means of restraining coal dust explosions (Section 9.1.11), the pasing of o coal dust explosion through bends in the galleries has to be discussed in more detail.

6.7.2. Foreign investigations

In the American *EM Bruceton* the network of the experimental galleries (Fig. 6.7) provides very good conditions for the observation of investigations on the passing of an explosion through a series of bends. In

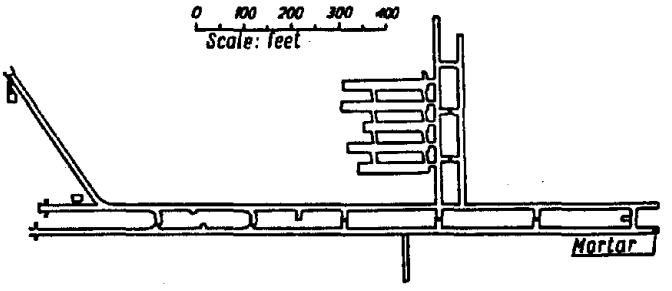


Fig. 6.7. Experimental galleries in the *EM Bruceton* of the Bureau of Mines, USA.

the publications of the Bureau of Mines [138], [139] data is given concerning the passage of the flame through a series of bends in the net of experimental workings. But no information is given on such details as the velocity of the flame or other parameters of the explosions. At any rate, as can be seen in Fig. 6.8, the explosions presented there developed easily passing through a series of bends. The explosion shown in Fig. 6.8*a* was initiated at the face of the main experimental gallery and the one shown in Fig. 6.8*b* in a crosscut.

Investigations carried out in the German *EM Tremonia*, and in mines in which coal winning activities were suspended [78], [121], likewise demonstrated that explosions pass easily through bends of workings. If a bend does not alter the direction by more than 90° no retardation in the development of the explosion is observed. The influence of bends becomes noticeable only when they exceeded 90°. As an illustration of the investigations carried out in the *Tremonia* mine the net of experimental workings are shown in Fig. 6.8c, at the level IV of that mine.

In Fig. 6.8*d* conditions are shown under which an explosion developed in the *Hagenbeck* mine where the pertinent workings go considerably upgrade. Unfortunately these investigations, conducted in very interesting

circumstances, supplied only general information on the velocity distribution of the flame; this is quite comprehensible when one considers the tremendous difficulties connected with such experiments.

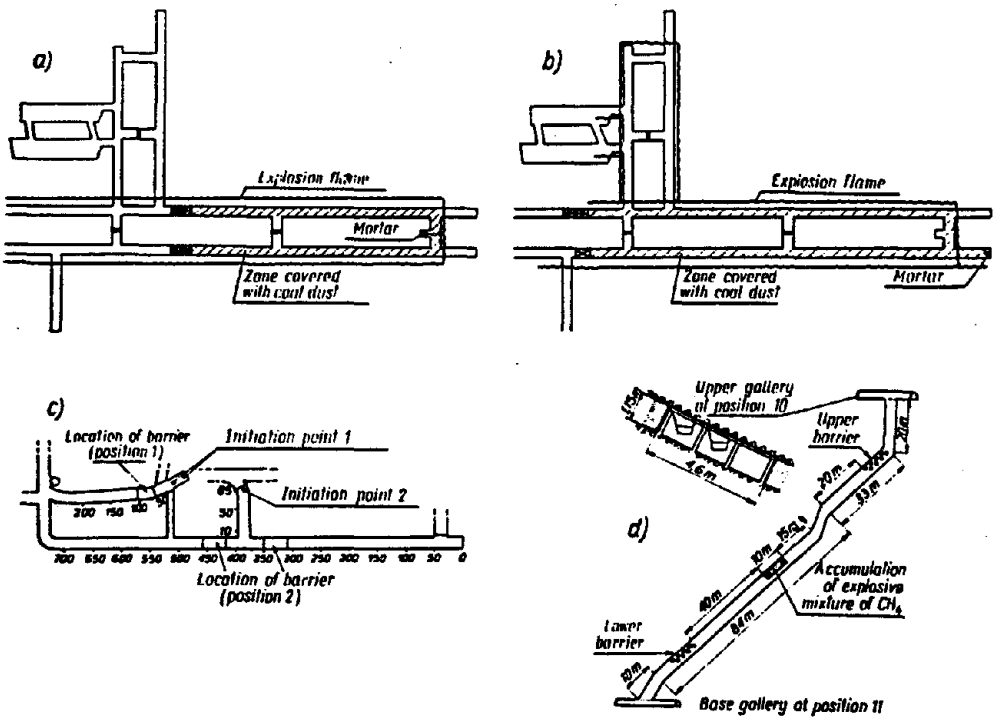


Fig. 6.8. Conditions for the development of explosions: *a* — in the galleries of the *EM Bruceton*, USA — explosion initiated in the crosscut connecting two parallel galleries; *b* — in the galleries of the *EM Bruceton*, USA — explosion initiated at the gallery's face; *c* — in the net of experimental workings at level IV in the *Tremonia* mine [121]; *d* — in a considerable acclivity of workings in the *Hagenbeck* mine [121].

6.7.3. Investigations in the *EM Barbara*

6.7.3.1. Conditions of investigations. As was explained previously on several occasions all investigations on the explosibility of coal dust, conducted on a large scale, are necessarily confined to the limits determined by the conditions under which experiments are carried out.

Conditions existing in the galleries of the *EM Barbara* allow to conduct the following investigations:

— in the development of an explosion in two directions the examinations of the passage of this explosion from a connecting gallery to both experimental galleries (Section 6.6),

— in the development of an explosion in one direction only the ex-

amination of its passage from the connecting gallery to either the 400 m, or the 200 m gallery,

— the examination of the passage of an explosion from the parallel gallery to the 400 m gallery through two bends.

The above experimental possibilities were taken advantage of to carry out more precise investigations on the passage of explosions through bends of workings.

6.7.3.2. The passing of a two-directional explosion from a connecting gallery to both connected galleries. In the course of the experiments described in Section 6.6 it was established that the development of the explosion in the connecting gallery had been rather slow on account of the fact that the velocity of the blast wave had been subjected to restrainments and, moreover this wave developed in two directions. On the other hand after the flame of the explosion had left the connecting gallery, and entered the 200 m and the 400 m galleries, the velocity of the flame increased considerably. This was due to the increase of the pressure at the faces of the two last mentioned galleries caused by the impact of the blast wave on the opposite walls of the galleries and, also, by a stronger turbulence at the faces.

6.7.3.3. The passing of an explosion through a one-directional bend of a gallery with a considerable narrowing of the gallery's cross sectional area. In Section 6.7.3.2 a two-directional explosion was discussed passing through gallery bends at which, locally, the cross sectional area of the gallery was narrowed. The course of this phenomenon was examined more thoroughly in an explosion developing in one direction only which — having been initiated in the connecting gallery — passed to the 400 m gallery.

The cross sectional area of the connecting gallery measured 4.01 sq m and that of the 400 m gallery 7.5 sq m, but the cross sectional area of the junction between the two galleries measured 1.4 sq m. These conditions proved to be of great importance to the investigations on the effectiveness of barriers discussed in Section 9.1.

It was established that the diminution of the cross sectional area, referred to above, at the joints between the experimental workings caused a serious obstacle in the way of the development of the explosion in the connecting gallery which found its expression in the low velocity of the flame in this working. The flame velocity was almost constant and averaged about 80 m/sec. After the passing of the explosion into the 400 m gallery the flame velocity grew very rapidly exceeding in some instances even the mark of 1000 m/sec. In Fig. 6.9 such a course of an explosion is shown by way of an example.

The phenomenon described here has been explained in Section 6.7.3.2. One should add, supplementing the explanation previously given, that at

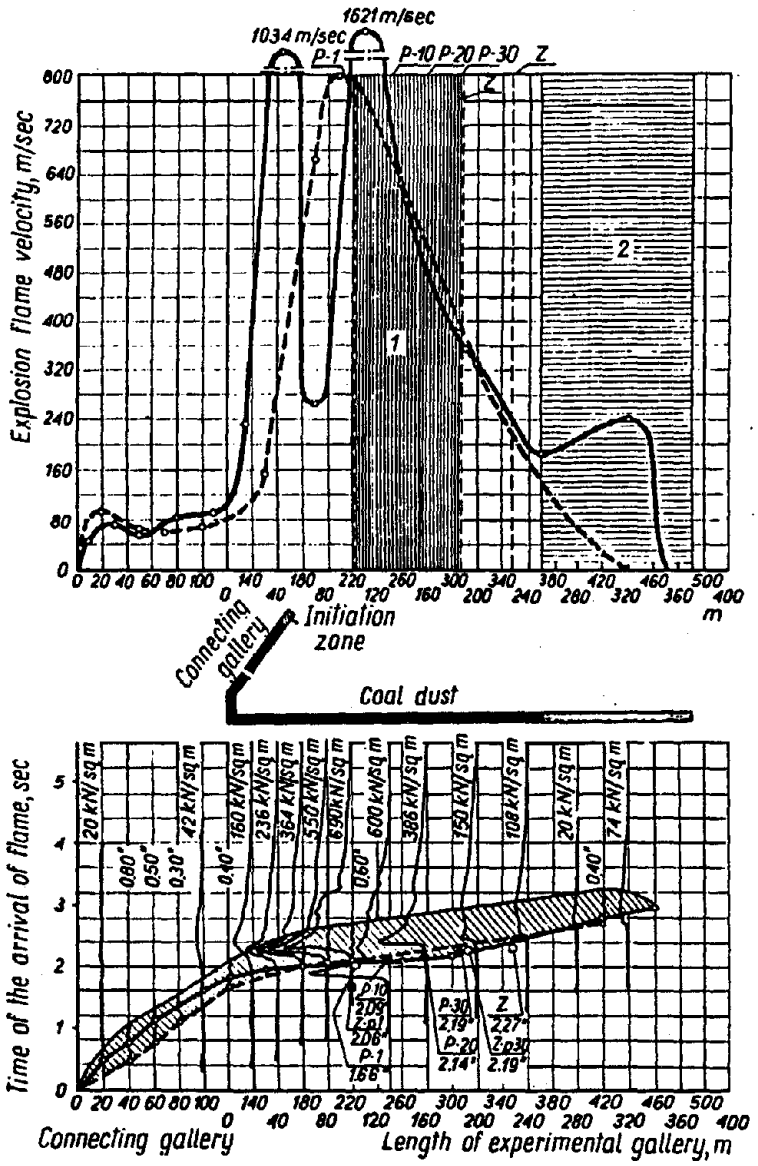


Fig. 6.9. A diagram of explosion No. 485 of the d85 *Barbara* coal dust, $n = 50\%$, initiated in the connecting gallery with the 10mPII initiator; *1* — barrier of 30 shelves, 1875 kg of stone dust, $Q = 250$ kg/sq m; *2* — protecting zone, 2478 kg of stone dust, $Q = 330.5$ kg/sq m; Z — wire net for recording the time at which barrier shelf breaks this net. Other symbols as in Fig. 6.4.

the time during which the blast breaks through the narrowed cross sectional area at the joint between the galleries a large cloud of coal dust forms itself in the 400 m gallery.

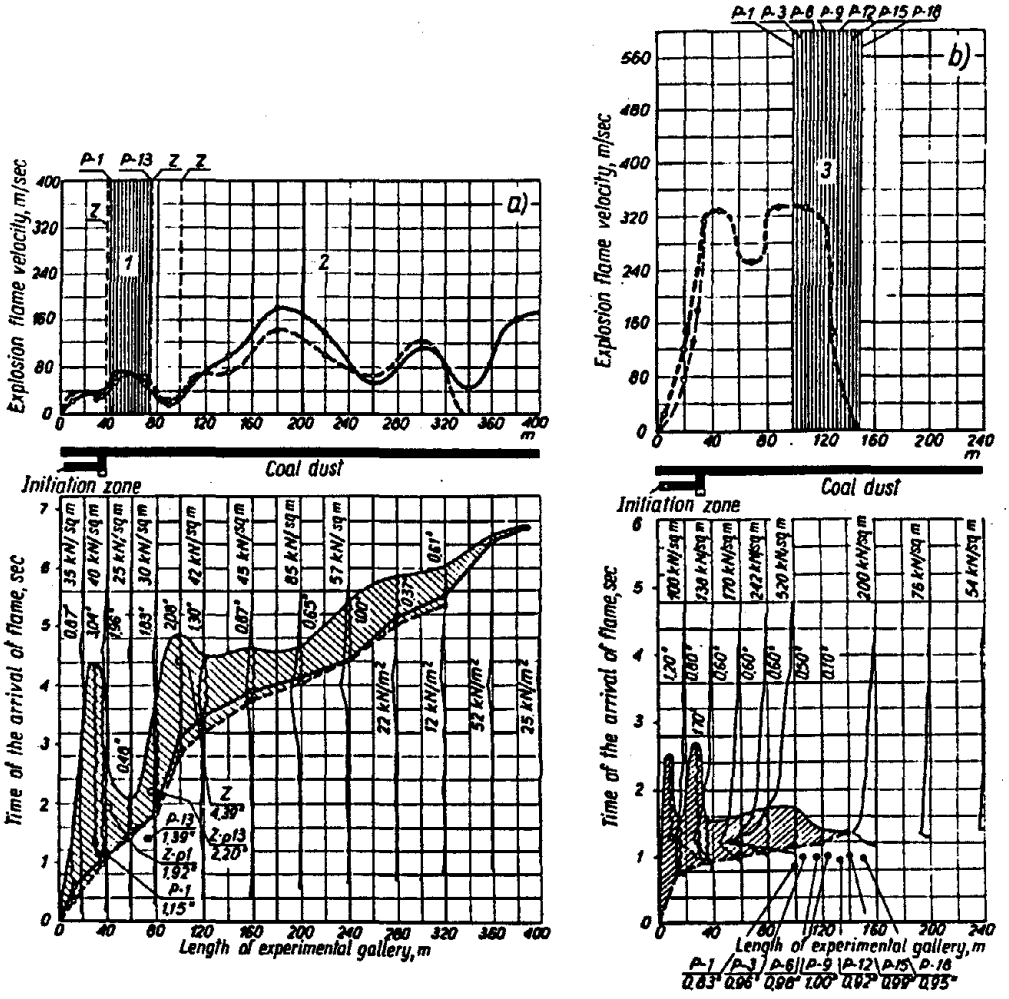


Fig. 6.10. Diagrams of explosions of the *d*25 *Barbara* coal dust, $n = 20\%$; *a* — explosion No. 149 initiated at the face of the parallel gallery with the 4mPII initiator; *1* — barrier of 15 shelves, 825 kg of stone dust, $Q = 110$ kg/sq m; *2* — storied 1×3 protecting barrier, 337.5 kg of stone dust, $Q = 45$ kg/sq m; *b* — explosion No. 498 initiated by the explosion of 50 cu m CH_4 9.5%, ignition close to the paper partition in the parallel gallery; *3* — barrier of 18 shelves, 1125 kg of stone dust, $Q = 150$ kg/sq m; *Z* — wire net for recording the time at which barrier shelf breaks this net. Other symbols as in Fig. 6.4.

6.7.3.4. The passing of explosions through bends of galleries having the same or slightly changed cross sections. This is the most common situation to be considered in connection with any possible explosion occurring in mines.

In order to examine the development of explosions in such situations experiments were carried out in which explosions were initiated in the

gallery parallel to the 400 m gallery (see Fig. 2.1). The length of the parallel gallery and of the crosscut amounted to 40 m and was equal to the distance between the face of the 400 m gallery and the crosscut.

The passing of explosions from the parallel gallery to the 400 m gallery had been examined many a time in connection with the tests of the effectiveness of barriers. All the pertinent experiments proved that the passage of an explosion from the parallel gallery to the crosscut and next from the crosscut to the 400 m gallery proceeds in almost the same way as in a rectilinear gallery. In the 400 m gallery the explosions developed more easily in the direction of the outlet than in the direction of the face of the gallery.

The passage of an explosion from the parallel gallery to the 400 m gallery is pictured, as an example, in Fig. 6.10*a*, *b*. In both of these cases barriers were used which will be discussed in a separate chapter.

The explosion shown in Fig. 6.10*a* developed only in the direction of the outlet of the 400 m gallery passing — without a noticeable diminution of its velocity — through both bends. The explosion shown in Fig. 6.10*b*, however, developed also in the direction of the blind face of the 400 m gallery — that is, it developed in two directions directly after entering the 400 m gallery from the crosscut. In order to simplify the diagram only the photoelectric registrations are given in it.

6.8. THE DEVELOPMENT OF AN EXPLOSION IN THE DIRECTION OF A BLIND END

6.8.1. The importance of the problem

An explosion of coal dust in the direction of a blind end is rather difficult since the shock wave and the blast wave are reflected from the face of the working and this has a hampering effect on the development of the flame in this direction. Moreover the products of combustion expand in the opposite direction — that is, in the direction of the network of workings or of the outlet of the experimental gallery. In consequence there is no pressure produced ahead of the flame front sufficiently conducive to an explosion of coal dust.

Even in cases in which an explosive mixture of methane fills a part of the gallery from the side of the blind end the flame initiated from the fresh air side develops in the direction of the blind end only with a velocity somewhat below 10 m/sec.

In many cases of explosions of coal dust in mines the network system of workings was such that the explosion developed lengthwise in a gallery from which blind end workings branched out. There were also cases of

explosions being initiated far off a blind end. In such cases it was very often found that the flame of the explosion either followed a very short road in the direction of a blind end, or did not develop at all in a blind working in spite of the presence in it of very dangerous coal dust.

The problem presented above is quite important in the conditions existing in mines and, therefore, in order to examine this problem more closely, investigations were carried out in the *EM Barbara* on the development of explosions in the direction of blind ends. The relevant tests were carried out mainly under two different conditions:

— dust explosions were initiated in a gallery parallel to the 400 m gallery; these tests having been already partly discussed in Section 6.7.3.4,

— dust explosions were initiated in the 400 m gallery.

A Schedule of Flame Velocities of Coal Dust Explosions Developing in
Arranged According to the Initiators Used and the Types

Initiator	$\frac{d \text{ — fineness of the dust}}{n \text{ — incombustible solid matter content}}$	Distance of the barrier from the gallery's face m	Intervals of the flame range m	Number of experiments in which the explosion flame reached the face vicinity
4mPII	$\frac{25}{\sim 20}$	—	10–0	1
	$\frac{25}{\sim 20}$	40–200	40–30 10–0	4
30mPII	$\frac{85}{67.5}$	40–160	30–10 10–0	1
	$\frac{85}{50}$	40–200	40–30 10–0	13
50 cu m CH_4 750 g of gunpowder	$\frac{25}{\sim 20}$	40–100	30–10 10–0	10
50 cu m CH_4 electric detonator	$\frac{25}{\sim 20}$	40–120	30–0 10–0	2
	$\frac{85}{\sim 20}$	40–80	20–10 10–0	11

Explanations: Range of the flame 10–0 signifies that the presence of the flame has been estab
presence was discovered. A result of this kind is interpreted as the arrival of the flame to a place

The range of the flame: e.g., 40–30 signifies that the presence of the flame has been established
face.

*The mean velocity of the flame is not given since the number of experiments carried out

6.8.2. The explosion of coal dust initiated in the gallery parallel to the 400 m gallery

Practically all experiments in this series were made in connection with testing the effectiveness of barriers located beyond the bends in the direction of the outlet of the gallery. The distance between the barriers and the face of the 400 m gallery oscillated from 40 to 200 m. The barriers were a hindrance in the way of the blast of the explosion causing a rise of the pressure in the zone in which the barriers were placed. This facilitated the development of the explosion in the direction of the face of the gallery, particularly when the barriers were placed at a distance not exceeding 100 m from the face.

Table 6.12

the Direction of the Face of the 400 m Gallery in Groups of Explosions of Coal Dust Irrespective of the Range of the Flame

Intervals of the maximum flame velocities m/sec	Mean maximum flame velocities m/sec	Intervals of the mean flame velocity	Mean flame velocities	Number of experiments
—	79.6	—	19.1	2
34.7–64.0	49.8	37.2–106.1	*	31
113.7–615.3	195.0	13.0–225.0	97.7	6
135.2–500.0	352.7	73.6–248.6	169.5	17
196.7–545.8	357.3	150.8–322.0	231.0	14
177.7–363.6	271.0	107.3–113.1	165.0	4
197.3–652.5	425.3	107.5–435.4	260.3	15

lished at the distance of 10 m from the gallery's face, yet at the front itself of the face no such close to the gallery's face.

at the distance of 40 m from the gallery's face but not discovered at the distance of 30 m from the

had not been sufficient to allow a reliable computation of the mean value of this velocity.

The development of an explosion in the direction of the face of the 400 m gallery is affected by the violence of the explosion in the parallel gallery and in the crosscut and on this factor, in turn, depends the pressure at the moment in which the blast enters the 400 m gallery from the crosscut. Taking this into consideration various explosion initiators were used in the parallel gallery such as 4mPII, 50 cu m CH_4 ignited with an electric detonator; 50 cu m CH_4 ignited with 750 g of gunpowder; and 30 mPII. For the same purpose — that is, in order to obtain various degrees of the violence of explosions, the *d*25 *Barbara* dust was used containing the natural quantities of incombustible solid matter, as well as the *d*85 *Barbara* dust with various contents of incombustible solid matter.

Altogether 89 experiments were carried out under the above described conditions.

A summary of the results is given in Table 6.12.

The results are scheduled in the most simple arrangement in which experiments are divided into groups according to the explosion initiators and the types of the dust used in the experiments irrespective of the range of the flame — that is, in every group there are included cases in which the flame reached the gallery face, as well as such cases in which the range of the flame had been shorter.

A classification of experiments into groups, according to the same range of the flame, gives a picture of less clarity. For this reason it is not presented here.

As can be seen from Table 6.12 the ease with which the flame could reach the face of the 400 m gallery clearly depended on the initiator and on the explosibility of coal dust. Thus when the weakest initiator, 4mPII, was used only in four out of 31 experiments the flame reached the face of the gallery. The same dust, when a strong initiator 50 cu m CH_4 ignited with 750 g of gunpowder was used, propagated the explosions to the face of the gallery in 10 cases out of 14. With a somewhat weaker initiator — that is, 50 cu m CH_4 ignited with an electric detonator — in two cases out of four the explosions were propagated to the face of the gallery.

With a very strong initiator, 30mPII, the *d*85 dust with incombustible matter content $n = 67.5$ percent only in one case out of six propagated an explosion to the face of the gallery while the same dust only with $n = 50$ percent, with the same explosion initiator, propagated to the face of the gallery 13 explosions out of 17.

With a weaker initiator — that is, 50 cu m CH_4 ignited with a detonator — the *d*85 "pure" dust propagated 11 explosions out of 15 to the face of the gallery.

The explosion initiator and the type of the dust also show a distinct influence on the velocity of the flame moving toward the face of a working

(Table 6.12); for instance, when the initiator used had been 4mPII the mean velocity of the flame of an explosion of the *d*25 dust amounted to 68 m/sec, while with the initiator 50 cu m CH_4 ignited with 750 g of gunpowder this velocity was 23 m/sec.

The following illustrations are given representing this series of experiments:

— in Fig. 6.11*a* the course of the explosion No. 117; the *d*85 dust; n = 50 percent; the initiator 30mPII;

— in Fig. 6.11*b* the course of the explosion No. 497; the *d*25 natural dust; the initiator 50 cu m CH_4 (9.5 percent of CH_4) ignited with 750 g of gunpowder;

— in Fig. 6.10*b* a diagram of the explosion No. 498; the *d*25 pure dust; the initiator 50 cu m CH_4 ignited with an electric detonator close to the paper partition.

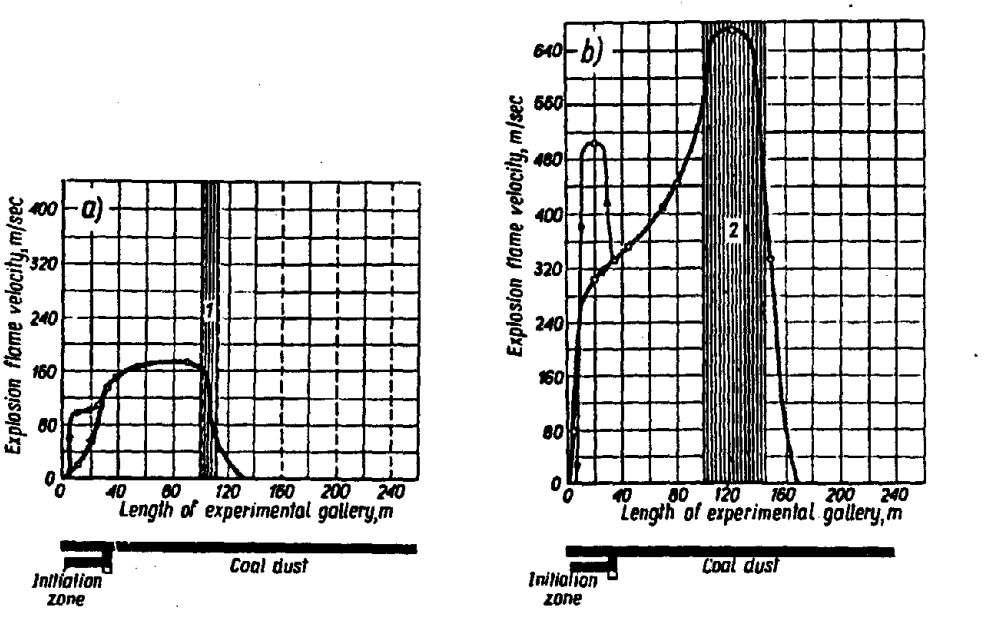


Fig. 6.11. Diagrams of explosions: *a* — explosion No. 117 of the *d*85 *Barbara* coal dust, n = 50%, initiator 30mPII; *1* — barrier of 5 shelves, 562.5 kg of stone dust, Q = 75 kg/sq m; *b* — explosion No. 497 of the natural *d*25 *Barbara* coal dust, n = 20%, initiator 50 cu m CH_4 (9.5%), ignited with 750 g of gunpowder; *2* — barrier of 16 shelves, 1800 kg of stone dust, Q = 240 kg/sq m.

The diagrams enumerated above refer also to investigations on the effectiveness of barriers in the case in which explosions were initiated at the face of the parallel gallery.

6.8.3. Explosions of coal dust initiated inside the 400 m gallery

In this series of experiments explosions had been initiated by firing of 750 g of gunpowder from a mortar placed in the direction of the gallery's face. In other words the direct initiator was used. In some of the experiments the initiator used was 10mPII.

The *d*25 *Barbara* dust — that is, the *d*25 dust with natural content of incombustible matter, was placed only in the section of the gallery between the mortar and the face, as well as in the parallel gallery and in the crosscut. In all experiments the easiest dispersion conditions were ensured, the dust being distributed on roof bars and on lateral shelves in order to facilitate the dispersion of the dust. From the side of the outlet of the gallery a protection zone was arranged covered with stone dust usually in the section from the 200th m to 300th m (counting from the face).

Under the above described conditions, examinations were made of the range of the flame and of its velocity in the direction of the face of the 400 m gallery, as well as in the direction of the face of the parallel gallery.

Explosions were initiated at a distance of from 60 to 200 m from the face of the gallery.

Nine experiments were carried out the results of which are summed up in Table 6.13.

Table 6.13

Results of Investigations on the Development of Coal Dust Explosions in the Direction of the Blind Ends of the 400 m Gallery and of the Parallel Gallery in the *EM Barbara*

Number of the test	Coal dust fineness	Distance between mortar and the front of the blind end	Protecting zone	Explosion flame range:	
				from the mortar in the direction of the 400 m gallery's outlet	from the mortar in the direction of the blind end of the 400 m gallery
	d, %	m	m	m	m
1389	85	60	200–300	20–40	—
1390	85	60	200–300	160–180	10–20
1391	85	100	240–340	220–240	0–10
1392	25	100	240–340	100–120	—
1393	25	120	240–340	20–40	—
1394	25	120	240–340	20–40	—
1395	25	140	200–300	100–120	100–120
1396	25	180	200–300	80–100	0–10
1397	25	200	220–320	120–140	0–10

In these nine experiments in four cases the flame reached the face of the 400 m gallery; in the same four experiments the flame reached also the face of the parallel gallery.

In four cases the flame did not develop in the direction of the face of the 400 m gallery; the range of the flame in these cases was quite inconsiderable.

It follows that the development of explosions in the direction of blind ends is not easy in spite of the fact that coal dust had been distributed so as to make the conditions particularly favorable to the development of explosions.

Very interesting are diagrams of explosions in which the flame reached the blind end in the 400 m gallery.

In Fig. 6.12*a* a diagram is shown of the explosion No. 1390 which had been initiated at a distance of 60 m from the face. The velocity of the flame in the direction of the face was very low its mean value amounting to less than 20 m/sec. In spite of the fact that coal dust was present in the 400 m gallery only in the section from 0 to 60 m and also in the parallel gallery and in the crosscut, the explosion developed in the direction of the outlet of the gallery and faded away only in the protecting zone. This was caused by the blast wave reflected from the blind end of the gallery which blew the dust in the direction of the outlet; the rarefaction wave, very probably, also played a certain part in the occurrence. The mean value of the flame velocity in the direction of the outlet amounted to 44 m/sec, the acceleration of the flame amounted to $a = 14.4$ m/sec. The diagram includes the regression equation expressing the relation between the distance and time.

In Fig. 6.12*b* a diagram is shown of the explosion No. 1391 initiated at a distance of 100 m from the face of the gallery. The course of the explosion was quite different from that presented in Fig. 6.12*a*. The explosion, now considered, developed in the direction of the blind end with high velocity which, measured by detonators, exceeded 600 m/sec, and measured by the photoelectric method did reach a maximum of 1300 m/sec. In the parallel gallery and in the crosscut the maximum velocity of the explosion was about 800 m/sec. The explosion developed also in the direction of the outlet of the gallery with a very high velocity; by the detonator recordings the maximum velocity amounts to about 2000 m/sec; according to the photoelectric registration this velocity was much lower. The explosion faded away only in the protecting zone. Of considerable interest is the exmination of the recorded static and dynamic pressures. Close to the blind end the pressure exceeded the measuring range of the pressure gauges; at the distance of 60 m from the blind end the static pressure was 240 kN/sq m and at the distance of 100 m from the blind end — 270 kN/sq m.

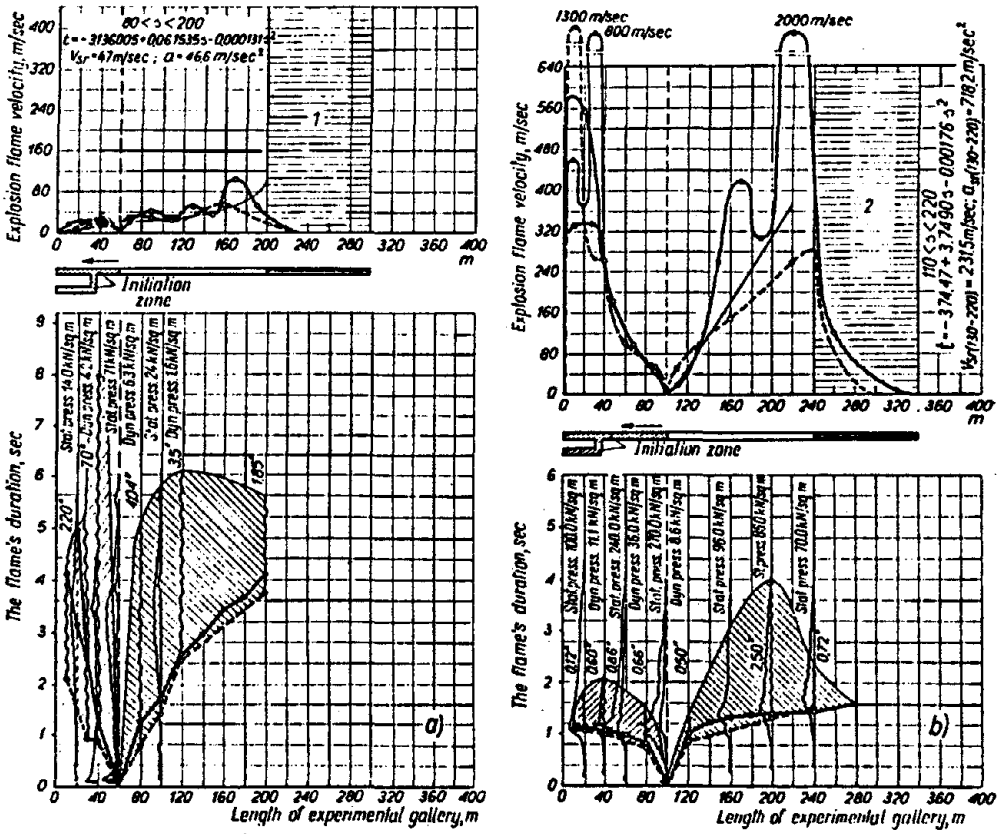


Fig. 6.12. Explosion diagrams: development of the explosion in the direction of blind ends: *a* — explosion No. 1390 of the *d*85 *Barbara* coal dust, $n = 16.5\%$, initiator: a shot of 650 g of gunpowder from the hole of the mortar in the direction of the gallery's face at the distance of 60 m from the face; *1* — stone dust protecting zone, $Q = 328$ kg/sq m; *b* — explosion No. 1391 of the *d*85 *Barbara* coal dust, $n = 16.5\%$, initiator: a shot of 650 g of gunpowder from the hole of the mortar in the direction of the gallery's face at the distance of 100 m from the face; *2* — stone dust protecting barriers, $Q = 275$ kg/sq m.

Apart from the blast wave, reflected from the blind end, the rarefaction wave certainly played a part causing the high velocity of the flame in the direction of the outlet; the flame velocity corresponded to the detonation of coal dust. Unfortunately there is no certitude whether the registered flame velocity is its true velocity. As was mentioned previously the velocity of the flame recorded by the photoelectric method was much lower. At any rate these investigations proved that the shifting of the location of the explosion initiator to a point more distant from the face of a gallery influences very strongly the development of an explosion.

When the mortar had been shifted to a longer distance from the blind

end, namely, to the distance of 200 m, an unexpected phenomenon of the detonation of coal dust in the explosion No. 1397 occurred (*Biuletyn PAN*, No. 5, 1971).

The increase of the length of the air column between the initiator and the blind end facilitates the development of an explosion in the direction of the blind end since the blast wave, reflected from the end of the gallery, must travel a longer distance and, besides, conditions become more favorable for the compression of the air column by the firing of explosives.

In order to avoid the development of an explosion in the direction of the outlet of the gallery the protecting zone with pure stone dust was made to begin at the distance of 20 m from the mortar in the direction of

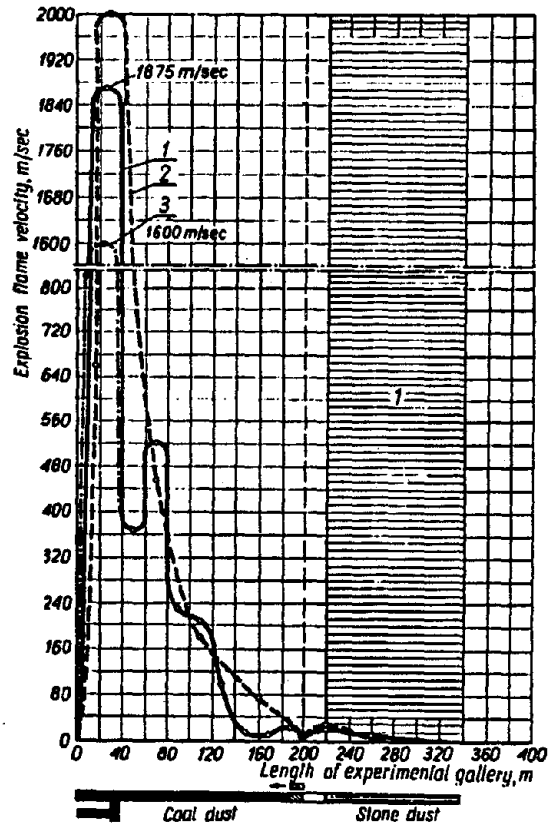


Fig. 6.13. Explosion development in the direction of the blind ends; a diagram of explosion No. 1397 of the *d*25 *Barbara* coal dust, $n = 19.5\%$, initiator 10mPII at the distance of 200 m from the face (the diagram shows the detonation of coal dust in the vicinity of the face of the 400 m gallery): *1* — detonator registrations curve; *2* — photoelectric registrations curve; *3* — detonator registrations curve in the parallel gallery; *1* (hatched area) — protecting zone, 2478.8 kg of stone dust, $Q = 330.5$ kg/sq m.

the outlet of the gallery. Apart from this, the experiment was made with the *d25 Barbara* pure dust and with the 10mPII initiator.

In Fig. 6.13 the diagram of the discussed explosion No. 1397 is given. The explosion developed in the direction of the blind end of the 400 m gallery and in the direction of the face of the parallel gallery. At first the development had been slow but later on it became very violent.

In the experimental gallery in the section between the 40th and the 20th m, counting in the direction of the blind end, the velocity of the flame determined by the photoelectric method was 2000 m/sec. In the section between the 40th and the 20th m, in the same direction, the velocity of the flame determined by detonators was 1875 m/sec. The recorded flame velocities differ from each other within the limits of the experimental error and, therefore, one is entitled to consider as a fact established in the course of the experiment that the velocity of the flame, close to the blind end of the gallery, amounted to about 2000 m/sec.

In the crosscut the flame velocity, determined by the detonators over a section about 8 m long, was 1600 m/sec.

On account of the fact that pressure gauges were damaged in the course of the experiment Fig. 6.13 does not show how the dynamic and static pressures were turning out. Thus a thorough examination of the phenomenon was made difficult. The detonation of coal dust in the vicinity of the face of the gallery was confirmed by the ensuing vast destructions.

In the wall of the gallery there was an emergency stopping built up of the St3s steel plate 32 mm thick. The door of this stopping had been strengthened by reinforcing ribs and cross braces. The clearance of the emergency stopping was 1.4 sq m. The explosion tore out a major part of the door of the stopping as shown in Fig. 6.14*a* (from the side of the gallery) and in Fig. 6.14*b* (in the direction of the gallery). Apart from this demolition of the emergency stopping with its entire hydraulic equipment deep cracks appeared in the concrete walls of the gallery. These concrete walls are about 50 cm thick and adhere directly to a very solid sandstone rock in which the experimental gallery had been driven.

In the course of many years of investigations numerous damages were recorded in the experimental gallery but never did they assume such dimensions. According to computations the shearing force, necessary to cut out a gap in the door of the emergency stopping, had to be equal to not less than 424 kN and the static pressure at the blind end to not less than 4100 kN/sq m.

The recorded phenomenon of the denotation of coal dust can be explained as follows: during the initial slow development of the explosion the blast wave reached the outlet of the gallery creating a reflected wave, which was a rarefaction wave, and behind this wave a pressure wave

moved into the gallery supplying oxygen to coal dust undergoing already the process of deflagration. This wave caused an adiabatic rise of the pressure in the explosive medium and a turbulent motion of the very well dispersed coal dust. In consquence conditions were created conducive to the detonation of the dust.

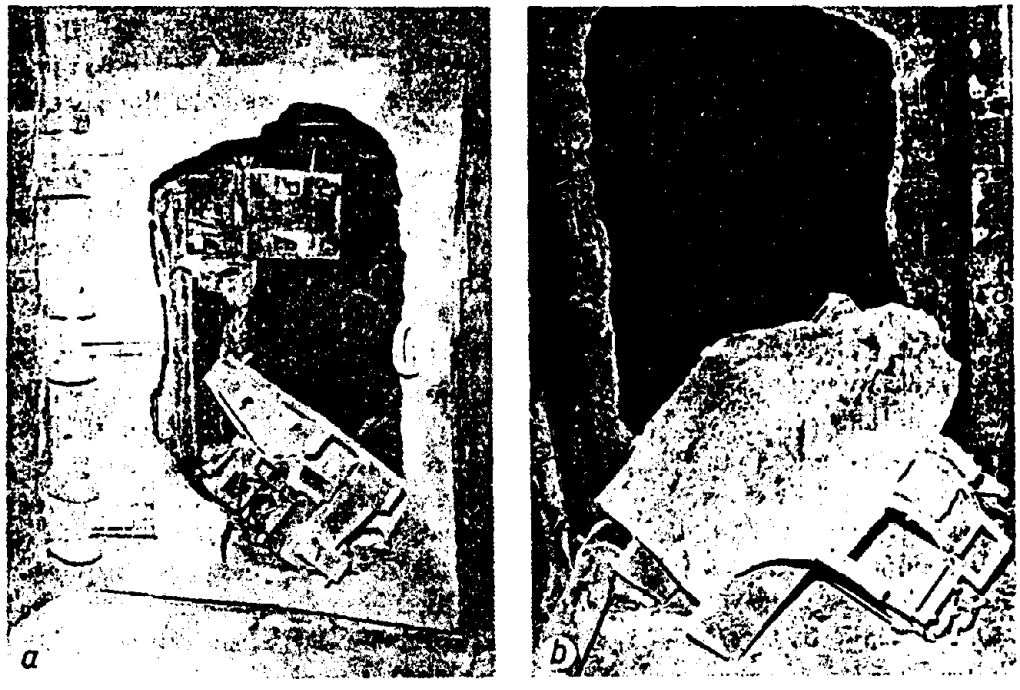


Fig. 6.14. The steel emergency stopping reinforced by ribs and cross braces destroyed by explosion No. 1397: *a* — view from the experimental gallery; *b* — view in the direction of the experimental gallery.

It ought to be underlined that the coal dust, which was made to detonate, had been of a relatively low degree of fineness and, at that, its content of incombustible matter had been equal to 19.5 percent in all, the ash content amounting to 12.7 percent, the content of the hygroscopic water being 4.3 percent, and of the free water 2.5 percent. A dust of this kind, according to opinions prevailing hitherto, theoretically should not be able to detonate.

Once it has been demonstrated that coal dust of relatively low parameters of explosibility did detonate; the possibility must be admitted of such phenomena occurring in practice especially when coal seams are made available for exploitation by dip roads in which conditions can be very similar to those described above.

The results of the investigations discussed here are given in Table 6.13.

They are of a considerable theoretical, as well as practical, importance. In these investigations the dust from the *Barbara* seam was used in which $V = 40.5$ percent and the content of incombustible solid matter n oscillated from 16.5 to 19.5 percent. Dispersion conditions were the easiest: coal dust was distributed on roof bars and on lateral shelves. The concentration of the $d85$ dust $q = 0.5$ kg/cu m, and of the $d25$ dust $q = 0.75$ kg/cu m. The direct explosion initiator was used: 750 g of gunpowder. In all experiments the barrel of the mortar was directed to the gallery's blind end. In none of the experiments did the explosion penetrate into the parallel gallery.

It would be very desirable to continue the investigations in order to elucidate in more detail the phenomena occurring under the described conditions. Unfortunately it was necessary to restrict the examinations to those scheduled in Table 6.13 because, as the explosion No. 1397 proved, experiments of the necessary kind might cause very big devastations. For the sake of accuracy it should be added that the demolitions caused by the above mentioned explosions were not restricted only to the face of the 400 m gallery.

As expounded in Section 2.3.3.2 the rarefaction wave, commonly called the reflected wave, did not influence in any observable way the course of coal dust explosions initiated at the face of the gallery and developing toward its outlet. In the case described here, however, it played a very important part as it was followed by a compression wave. The rarefaction wave by itself had but a slight influence on the movement of the flame facilitating only, to a very insignificant degree, the development of the flame in the direction of the outlet since the flame has been always quenched on its way in this direction in the protecting zone containing stone dust.

6.8.4. Investigations carried out by the Bureau of Mines

A series of investigations was carried out in the *EM Bruceton* on the development of coal dust explosions in the direction of blind ends [127].

In these investigations the range of the flame was being determined but no other parameters of explosions were measured. It was established that, while the development of an explosion toward a blind end is far from being easy, yet, in many instances, it has been recorded that explosions did reach the face of the gallery. Results of the experiments are given in diagrams:

— in Fig. 6.15*a* an explosion, initiated at the face of the main experimental gallery, did not reach the face of the parallel gallery,

— in Fig. 6.15*b* the flame of an explosion, initiated at the face of the lateral gallery, did not reach the blind ends of mine rooms but reached the faces of the parallel experimental galleries (which might have been due to secondary movements of gases), .

— in Fig. 6.15*c* the flame of an explosion, initiated at a corner of connected mine rooms, had not been hindered in its development except that it was kept in check as the result of the workings being dusted with stone dust to make the total content of incombustible solid matter in the mine dust go up to 68 percent.

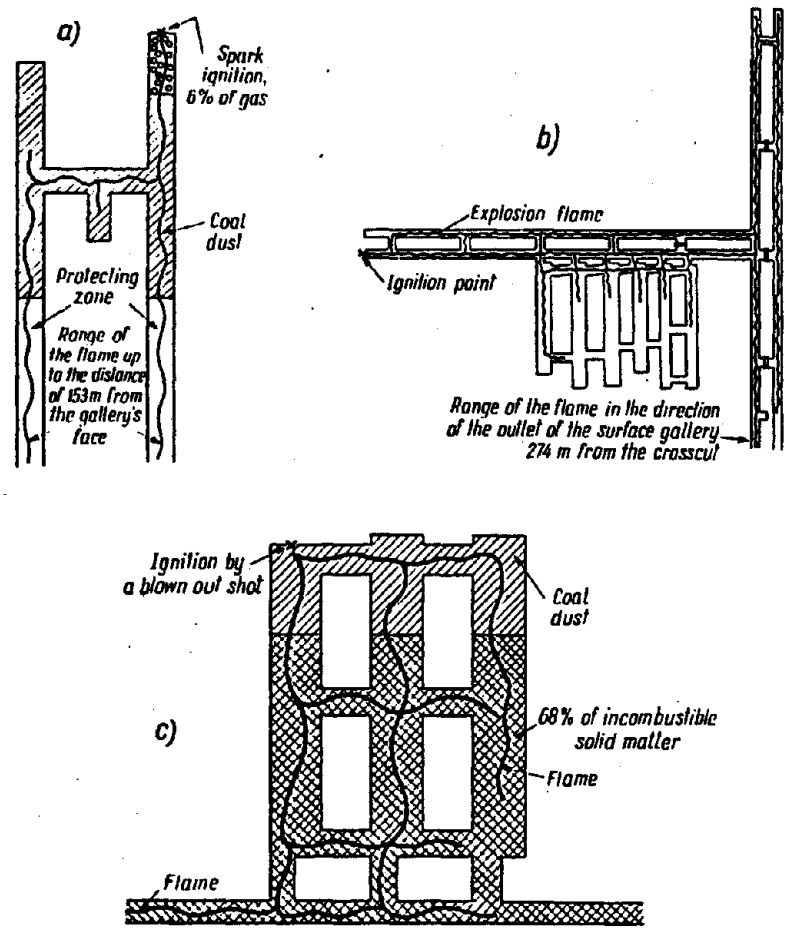


Fig. 6.15. Examination of the development of explosion in the *EM Bruceton*, USA: *a*, *b* — in the direction of blind ends; *c* — in connected mine pillars.

American investigators are of the opinion that the flame of explosion would reach blind ends if the atmosphere contains an explosive mixture

of methane and that it will not develop in the direction of blind ends if the workings contain coal dust only. The above opinion is not supported by the results of investigations carried out in the *EM Barbara* discussed heretofore in Sections 6.8.2 and 6.8.3.

— in Fig. 6.15b the flame of an explosion, initiated at the face of the lateral gallery, did not reach the blind ends of mine rooms but reached the faces of the parallel experimental galleries (which might have been due to secondary movements of gases), .

— in Fig. 6.15c the flame of an explosion, initiated at a corner of connected mine rooms, had not been hindered in its development except that it was kept in check as the result of the workings being dusted with stone dust to make the total content of incombustible solid matter in the mine dust go up to 68 percent.

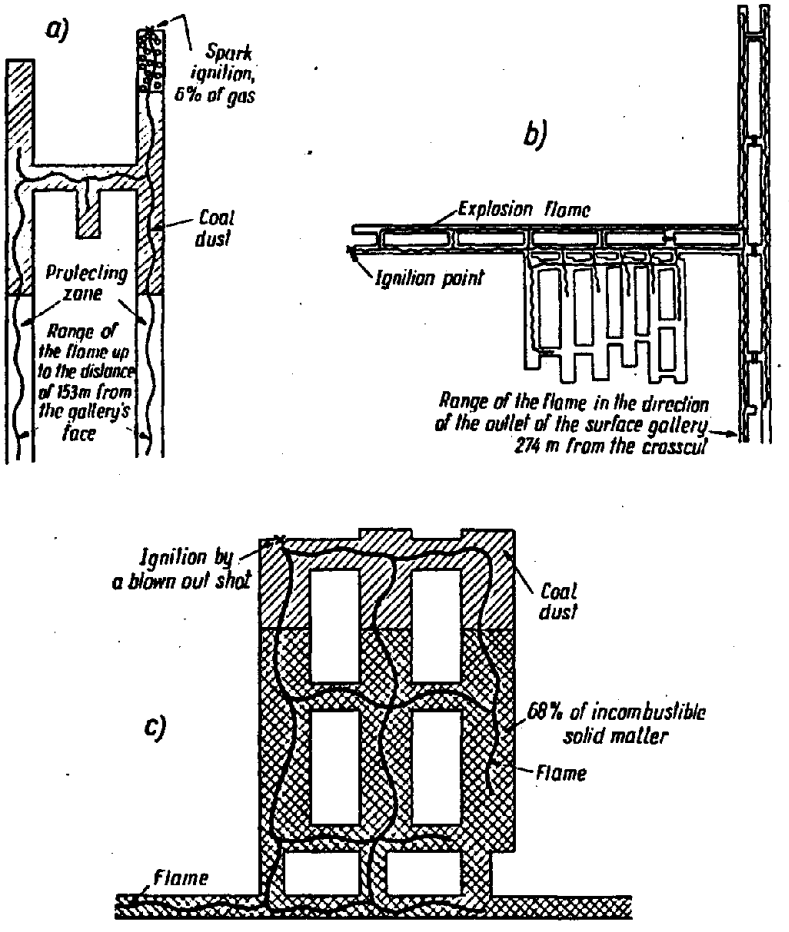


Fig. 6.15. Examination of the development of explosion in the *EM Bruceton*, USA: *a*, *b* — in the direction of blind ends; *c* — in connected mine pillars.

American investigators are of the opinion that the flame of explosion would reach blind ends if the atmosphere contains an explosive mixture

carbon monoxide should be mentioned as the first among the fatal consequences. Concentrations of carbon monoxide oscillate within wide limits depending on the character of the explosion, the disposition of workings and the ventilation conditions but they are always above the lethal concentrations. In particularly bad cases, after the passing of the explosion flame, the carbon monoxide content in the atmosphere comes to 12 percent. There is no need to specify how great are the quantities of carbon monoxide produced in the outcome of an explosion flame passing over a long distance. The carbon monoxide, carried by the air flow, often reaches flats in which the workers are not even aware of the explosion, the gas causing death casualties. Apart from the quantities of carbon monoxide a tremendous role is obviously played in such cases by the conditions of the workings, the route over which the air poisoned with carbon monoxide progressed, the ventilation, and the number of workers who happen to be present where the poisoned air flows. World statistics of coal dust explosions supply an irrefutable evidence of the fact that the most numerous casualties resulting from coal dust explosions are caused by fatal carbon monoxide poisoning. By way of an example it may be said that, during the explosion in the *Heinitz* mine (Rozbark) in the year 1923, a total of 145 men lost their lives. Of this number 118 men were poisoned to death by carbon monoxide, 23 men died in direct consequence of the explosion — that is, through the action of the flame and blast, and four men were lost in the course of the rescue activities.

Of recent disasters reference can be made to data concerning the explosion in the *Mikaiwa* mine in Japan, in the year 1963, in which 457 miners lost their lives. Of the above number only 20 miners were the direct victims of the impact of the explosion; all the rest were fatally poisoned by carbon monoxide. A large number of similar examples can be cited but the two explosions mentioned above are a sufficiently convincing proof of the poisonous role of carbon monoxide.

Further, it is necessary to mention that the situation during explosions is made worse by such facts as the knocking out of ventilation dams and the falling in of roofs which cause changes in the normal circulation of the air. In consequence the air becomes poisoned with carbon monoxide over long stretches of the mine roadways. Moreover the changes in the normal course of ventilation make it difficult to ascertain the situation for the purpose of planning rescue activities and they impede the rescue action itself.

The blast of an explosion always reaches farther than the explosion flame and causes casualties by its impact. In mine workings it acts simply as a hurricane. The motion of gases is not at all a one-way motion. Immediately behind the front of the blast wave a rarefaction wave appears

and makes the gases move in the opposite direction. The course of the blast waves in mine workings becomes ultimately so complicated, especially during violent explosions, that men at locations farther afield from the place of the explosion report having heard several explosions. This comes from the fact that the sound waves, as well as blast waves, reach them from various directions. As regards the blast produced by coal dust explosions it should be stated that, if the flame velocity is high (about 1100 m/sec), the dynamic pressure of the blast wave amounts to about 2200 kN/sq m.

The explosion blast which has been discussed heretofore causes on its way the more damage the stronger is the explosion. Ordinarily it will knock out the support and cause the roof to fall in. The caving in of roofs occurs very easily since — as has been mentioned before — the blast wave is followed by the rarefaction wave which facilitates such accidents. The knocking out of supports and the caving in of roofs cause tremendous difficulties for rescue parties. The rescue actions are conducted as a rule under very dangerous conditions.

It would not be proper to leave unmentioned the enormously hard duty of searching for the corpses of the victims under the fallen in roofs. It is usual for this duty to be discharged under conditions which are generally dangerous. The sorting out of the debris of fallen roofs in the search of the corpses of victims often is, unfortunately, a hazardous occupation.

A considerable step forward was made in the task of facilitating the search for men cut off by, or buried under, the fallen in roofs in mines when a device had been designed for finding men under the debris. The device works on the principle of the emission of impulses. The electronic apparatus in question consists of three basic sets:

— the personal miner's location transmitter,

— the special radio receiver working within the range of the operating frequencies of the transmitters mounted in the batteries of the miners' cap lamps,

— the direction finder attachment for determining the direction and the location of the source of the impulses.

The miner's personal location transmitter of the *GON* type is a part of the individual equipment of every underground worker of a mine. It is placed in the battery part of the miner's cap lamp. It radiates a continuous unmodulated electromagnetic wave. The radio signals, sent out by the location transmitters, are received by a special radio receiver working within the operating range of the transmitters. The radio receiver in question, together with the attached direction finder, is used by the rescue teams. With the aid of the direction finder the direction is determined

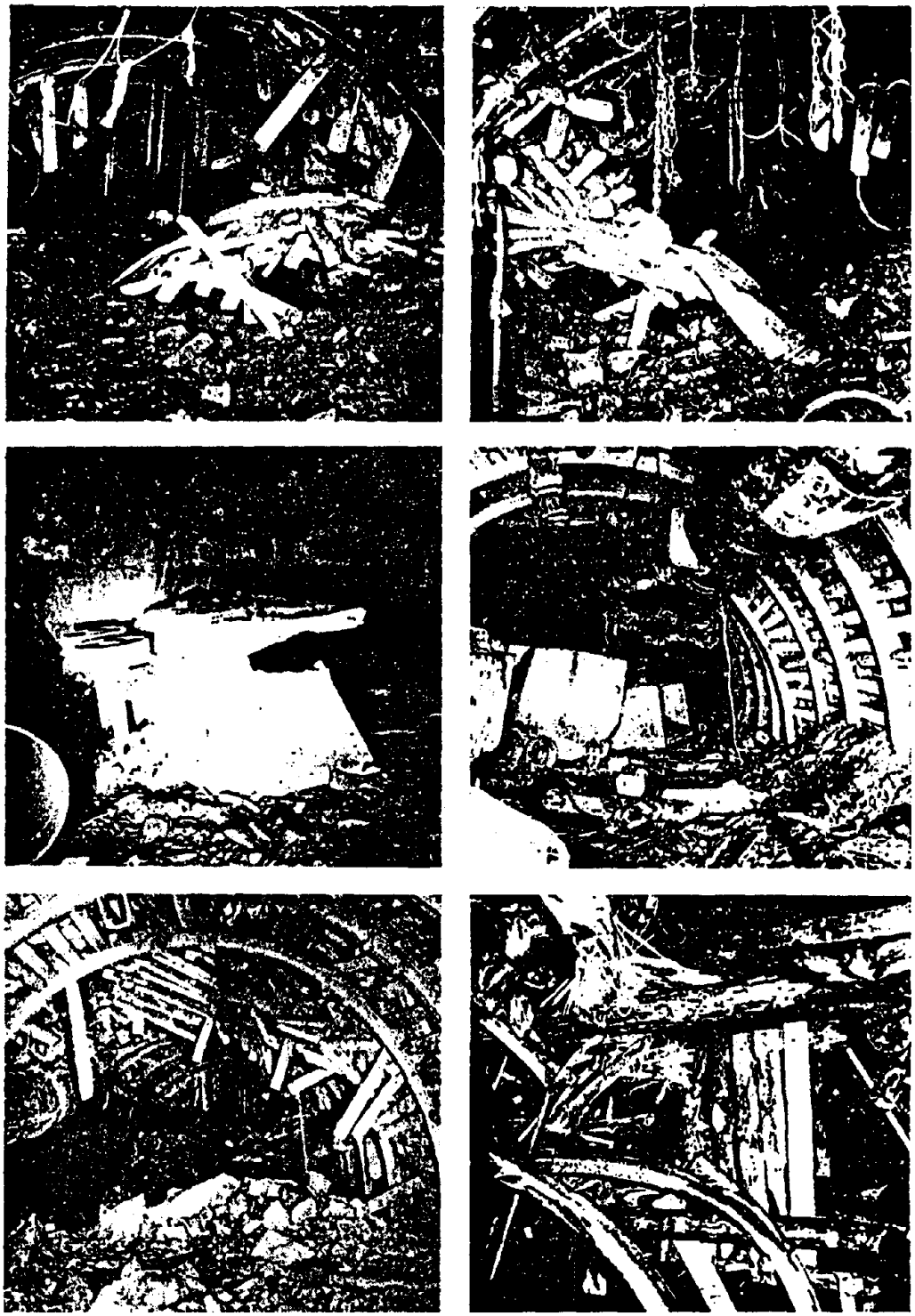


Fig. 7.1. Views of workings after coal dust explosions in mines.

from which the signals are sent out. When the directions are determined from which two or more signals are received the place can be located and marked on the plan where men have been covered up by the debris and thus the distance and the direction can be fixed in which the rescue team should proceed. This method of searching for men under and behind fallen in roofs of mine workings allows to detect the transmitter signals in any mining conditions from a distance of about 30 m.

As an example of the difficulties connected with rescue activities the loss of two rescuers may be cited after an explosion in the *Wanda Lech* mine in which there were no casualties caused by the explosion itself. Two rescuers were killed when they went, together with other members of their team, to reconnoiter the field in which the explosion took place particularly to find out whether a fire did, or did not, break out and generally to ascertain the condition of the workings after the explosion.

Workings, through which an explosion has passed, present a very varied sight. When explosions are weak it happens occasionally that the support is left altogether intact and that, apart from the victims of the disaster, no noticeable damages have been effected. When explosions reach shafts the shaft equipment becomes damaged. There were cases recorded in which the headframes of shafts had been demolished. Even on the surface people can become victims of explosions. When the seams are made accessible by dip roads, explosions can always easily reach the surface. Figure 7.1 shows, by way of example, photographs of mine workings after the passage through them of coal dust explosions. The damages to the roof are of particular interest since they create a special hazard for rescuers.

Explosions are often the cause of fires. The flame of a coal dust explosion, even in the straight 400 m experimental gallery in the *EM Barbara*, persists for a relatively long time even as long as 10 sec. In complicated mine workings the duration of the flame may be longer and a fire can easily get started. It is worth mentioning that when the experimental gallery of the *EM Barbara* was timbered there were instances of the timbering being set on fire by explosions. A fire is always dangerous but when it starts in consequence of a coal dust explosion the danger is much more serious because — apart from being an additional impediment in the way of the rescue activities — it makes very difficult the determination of the zone affected by the explosion and finding the exact location of the fire. The workings become filled in such cases with the smoke of the fire in addition to the explosion products. A situation of this kind may cause fatal casualties as in the previously discussed case of the *Heinitz* mine disaster in which the death of four rescuers had been caused, among other factors, by the smoke of the fire.

The consequences of an explosion depend in a great measure on the state of the ventilation of the area affected by the disaster. A proper ventilation of the flat can lower considerably the number of casualties. As an example one may mention the explosion in the *Walenty Wawel* mine in the year 1967. The flame in this explosion passed a total distance of 350 m. There were 38 men present within the area of the explosion all of whom were in danger of the carbon monoxide poisoning. The fatal casualties were limited to four miners only because the correct ventilation of the flat made it possible to remove very quickly the air poisoned with carbon monoxide.

Disasters do not merely kill men: they also cause harm and bring sorrow to the families of the victims and create a feeling of despodency not only among the workers of the mines which are directly affected, but also in the mining circles at large.

Disasters and their consequences adversely affect the psychology of miners and impair their confidence in the effectiveness of the measures taken for the prevention of explosions. This lack of confidence extends to include the management of mines. Considerations of social equity, as well as the necessity to liquidate the moral consequences of disasters, make it imperative that the most careful and impartial investigation of the causes of every disaster be carried out; that all the necessary conclusions be drawn and the most effective steps taken to prevent such disasters in the future.

Unfortunately the world history of mining shows that the above requirements, indisputable and obvious as they are, not always had been complied with in the past. Great disasters in mines which, unfortunately, still occur in our times prove that experience gained in the past is not being utilized consistently in the mining practice. After a disaster safety rules are for a time looked upon as requiring exact performance. With the passing of time this attitude often slackens.

7.2. OBSERVATIONS MADE AFTER THE EXPLOSIONS WITH A VIEW TO DETERMINING THEIR RANGE

After the explosions investigations were carried out in the mine by workers of the *EM Barbara* with the aim, among other things, of determining the range of the flame and of examining the residues of coal dust explosions in the experimental galleries, as described in Section 2.3.2. Generally, it was possible to determine the range of the flame by means of coke grains found in the gallery. In the majority of cases the range of the flame, ascertained in this way, had been consistent with the observed sings of the flame's action which appear with the utmost clearness on objects

the surface of which is large in relation to their mass, such as, for example, hair, bits of paper, etc.

The melting out of resin from timber and the parching of pit props and boards were observed repeatedly. Such phenomena take place where the flame's action persists a longer time. Mistakes can be made when determining the range of the flame on the basis of the presence of coke grains since the dust is raised by the motion of gases not only during explosions but also after their extinction. The gases move in one and then in the opposite direction, in several and even in numerous turns under the influence of rarefaction and reflected waves.

In the experimental explosions, as well as after disasters in mines, agglomerations of coke were discovered where the violence of explosions had been augmented. Actually these agglomerations were situated mainly on the side of the point at which the violence of the explosion increased opposite to the direction from which the explosion had developed. Similar phenomena were observed by American investigators after explosions in mines in USA [127].

After certain experimental explosions, as well as after disasters in mines, large accumulations of soot were observed educed from the smoke of firedamp or coal dust explosions. Identical observations were made in other countries.

In the *EM Bruceton* interesting studies were made of the coking of coal dust after explosions [127]. These studies were only qualitative in their character; nevertheless, they led to the establishment of facts some of which are compatible with the results of investigations carried out in the *EM Barbara* (Section 2.3.2).

Within the zones through which the flame moves at a high velocity no coke, or a very small quantity of it, is found.

In the experiments made in the *EM Barbara* large quantities of coke grains were found also in zones in which flames moved with high velocities though it has been established that the duration time of the flame exerts an obvious influence on the formation of the coke (Section 2.3.2).

It would appear from the results of American investigations that during violent explosions the coal dust participating in them undergoes a complete combustion. According to American investigations the presence of coke is an indication of the passage of the flame, though the flame of an explosion can pass a working without causing the formation of coke. Investigations carried out in the *EM Barbara* show that coke was always present after the passage of the explosion flame.

According to American investigations coke is not formed when the dust contains more than 50 percent of incombustible matter. In the investigations carried out in the *EM Barbara* mine dust containing as much

as 72.5 percent of incombustible matter was found to contain, after the explosion, 34.5 percent of coke grains.

According to American investigations lignites do not produce coke after explosions. This contradicts the results obtained in the *EM Barbara* where it has been established that, after the passage of the explosion flame, coke grains were formed also from lignite dust.

8. THE WAYS OF SUPPRESSING THE DANGER OF COAL DUST EXPLOSIONS

8.1. DEFENSE LINES AGAINST THE HAZARD OF COAL DUST EXPLOSIONS

In the present state of knowledge and technology it is not possible to combat the hazard of coal dust explosions in mines in just one single way. This would have been possible only if the subterranean exploitation of coal were to be replaced by its subterranean gasification. Such methods, however, have not been productive, so far, of economic results that could justify the replacement by them of the hitherto used methods of exploiting coal.

Various ways can be used to combat coal dust explosions. The author of this work had been always convinced that an ample series of defense lines ought to be opposed to the hazard in question. In order to avoid the terrible consequences of firedamp and coal dust explosions not a single line of defense can be neglected.

In spite of their complex character and diverse causes coal dust explosions undoubtedly can be quite effectively overcome. The present state of knowledge and the practical methods already worked out make this task wholly realizable. However, this formidable hazard ought to be suppressed by all the available lines of defense to which the following measures are counted:

(1) Limiting the formation of coal dust.

(2) Removing coal dust.

(3) Preventing the dispersibility of coal dust — that is, preventing the formation of an explosive system.

(4) Preventing the possibility of the ignition of the primary coal dust cloud.

(5) Restraining the development of coal dust explosion — that is, preventing the propagation of coal dust explosion.

(6) Limiting the range of coal dust explosions by stunting the progress of the already developed explosions.

(7) Checking up on the hazards of coal dust explosions.

(8) Issuing regulations on suppressing the hazard of coal dust explosions.

(9) Carrying out scientific research work on the improvement of methods of suppressing coal dust explosions.

The fact that coal dust explosions hold the regrettable record among the causes of mining disasters imposes upon the world coal mining industry the duty of maintaining steadily on a proper level all of the above named defense lines.

8.2. LIMITING THE FORMATION OF COAL DUST

8.2.1. General information

The possibilities of reducing the formation of coal dust will be discussed here in the order in which the sources of its formation were given in Section 1.2.

Generally, it ought to be said that, unfortunately, the fight against the formation of coal dust in underground mines is inadequate and very seldom conducted according to a plan. In the technological processes, in which coal dust is incidentally produced, the technological effects of these processes play a decidedly paramount role while the question of keeping under control the degree of the fineness of coal does not receive sufficient attention. This view may appear to be rather pessimistic but the author's observations of the mining practice tend to confirm it.

There are many ways (methods) already worked out of reducing the output of fine coal and, in consequence, also of coal dust but they are not used in spite of the fact that their introduction into the mining practice is possible. The size of the coal output is the decisive factor, and the formation of coal dust is simply the result of using this or that particular technological process. Much can be done in the matter of reducing the formation of coal dust. The present state of knowledge and of technology presents wide possibilities in this matter. Naturally the formation of coal dust in mines cannot be avoided, nevertheless if the technical inventiveness were directed more specifically to the problem of reducing the formation of coal dust, there is no doubt that good results would have been attained.

In order to avoid any misunderstandings it ought to be explained that in this chapter the only subject to be discussed is the reduction of the formation of coal dust and that this subject, contrary to all appearances, cannot be always identified with the problem of the quantities of coal dust present in mine workings.

The quantities of coal dust actually present at particular places in

mine workings depend in a large measure upon the steps taken to reduce the dispersibility of the dust, or to remove the dust; this is discussed in a separate chapter. When discussing the quantities of the produced coal dust not only the coal dust which remains in mine workings is meant but also the coal dust which, together with the whole output, is drawn out of the mine to the surface.

8.2.2. Limiting the quatity of coal dust produced in the course of coal winning

8.2.2.1. Possibilities of reducing the formation of coal dust in the course of mechanical coal winning. In the mechanical winning of coal, particularly when combined cutter loaders are used, the quantity of coal dust is quite large.

A slower movement of the cutting elements, if their power were increased, could bring about a reduction of the quantities of fine coal and coal dust produced, yet the designers of combined cutter loaders are always interested in the economic effects of the work of their machines and the problem of the fine coal incidentally produced is not, unfortunately, taken into consideration at present when new types of combined cutter loaders are designed.

In effect combined cutter loaders produce large quantities of dust and there is no real chance at the present time to have these quantities seriously reduced. Likewise, there is no question of a real progress in the reduction of the quantities of dust produced by cuts which, anyhow, are used less and less now in our mines.

In order to compare the quantities of fine coal produced by combined cutter loaders on the one hand, and coal planers on the other, it would be necessary to examine the quantities of particular fractions produced per ton of mined coal. Unfortunately, no results of such examinations are known so far.

According to information received from the Construction and Mechanical Plant of the Coal Industry, the drum shearers produce 60 to 35 percent of fine coal when mining Upper Silesian coal, while coal planers produce about 30 percent of fines of the same coal.

The results of German investigations on this subject [120] are given in Table 8.1.

The production of coal dust when mining coal with combined cutter loaders and coal planers is obviously of great importance to the problem of the hazard of coal dust explosions. Moreover, the production of dust < 5 μm is very important on account of the air becoming dusty with a harmful dust.

Table 8.1

Yield of Small Coal Fractions during the Work of Drum Shearers and Coal Planers (after F. Melsheimer [120])

Type of machinery	Fractions of small coal		
	10–0.5 mm	<0.5 mm	<10 mm
	yield, %		
Drum shearer	23.8–45.6	5.2–17.4	29.0–63.0
Coal planer	33.0–39.9	11.2–14.2	44.2–54.1

8.2.2.2. Possibilities of reducing the quantity of fine coal produced in the course of coal mining by means of shotfiring in mines. The possibilities of reducing the quantity of the dust in the course of shotfiring are much greater than they are in the case of the mechanical mining of coal.

First of all reference ought to be made to the experimental preparation of shotfiring specifications according to instructions issued by the *EM Barbara* [69]. According to Kobyliński, the yield of fine coal may be reduced by about 15 percent when a correct experimental preparation of the shotfiring specification is resorted to.

Explosives produce greatly varying quantities of dust depending on the detonation pressure and the method of shotfiring. Naturally, an explosive produces the more coal dust the "stronger" it is, to use a common parlance expression, meaning: the higher is its detonation pressure. The choice of an appropriate explosive can reduce considerably the yield of fine coal and, consequently, also the yield of coal dust. Kobyliński demonstrates this very clearly in his work [103]. Through the selection of the appropriate explosive he obtained a reduction of the fine coal yield by about 5 percent.

It is possible to reduce very materially the yield of fine coal and coal dust by using the method of shotfiring under the presssure of water. According to the work of Stranz [164] the yield of fine coal by using this method can be reduced by 27 percent.

According to Kobyliński [103] shotfiring with a cut reduces the yield of fine coal by 5 percent.

Naturally, the reduction of the yield of fine coal automatically reduces the yield of coal dust.

Shotfiring with an empty space left between the charge of explosive and the tamping can also have effect — under favorable conditions — upon the reduction of the yield of coal dust.

More details concerning the influence of shotfiring operations on the yield of fine coal can be found in the above mentioned publications [103], [164] and in other sources.

In this book, dedicated to the problem of coal dust explosions, shotfiring operations are mentioned only as a factor in the production of coal dust, and the rudimentary means are indicated of reducing this production.

To shotfiring operations are counted also the operations of winning coal by using compressed air or by the Cardox method.

In these methods no explosives are used and, therefore, the detonation pressure does not appear at all; moreover, the pressures of gases are low. In consequence the yield of coal dust is not large. The lowest yield of fine coal is achieved through the method of winning coal by the use of compressed air at a working pressure of 60 to 70 MN/sq m.

8.3. THE REMOVAL OF COAL DUST

8.3.1. General information

The smaller is the quantity of coal dust in mine workings, the easier it is to combat the hazard arising from its presence. This principle ought not to be forgotten.

The quantities of stone dust which must be added to coal dust, in order to fulfil regulation requirements, grow very considerably with the increase in the quantities of coal dust. Simple arithmetical calculations show this as clearly as the figures cited below by way of examples. It is particularly easy to make a mistake by underestimating the quantities of stone dust which must be added to coal dust in order to raise relatively little its content of incombustible matter. If the density of coal dust in a working $q = 1$ kg/cu m and the incombustible matter content in it $n = 20$ percent, then, in order to fulfil regulation requirements — that is, to bring this content n to 80 percent, it is necessary to add 3 kg of stone dust per cu m of the working.

When the gallery is 200 m long and its cross section measures 10 sq m, the dusting of this gallery requires 6000 kg of stone dust. But when, in the same gallery, the density of the same coal dust $q = 0.5$ kg/cu m, only 3000 kg of stone dust are necessary to comply with regulations requirements. If the density of the dust q in the same gallery equals 0.5 kg/cu m, but $n = 70$ percent, then to fulfil the regulation requirements, namely, the raising of the value of n to 80 percent in the entire gallery, 500 kg of stone dust must be used.

These elementary examples confirm the importance of the removal of coal dust to combating the hazard connected with its presence.

It is proper to stress the fact that, in the case of very large accumulations of coal dust, the quantities of stone dust necessary in order to

comply with regulation requirements are so great as to make the fulfilment of the requirements practically impossible.

Taking into consideration inclined workings in which the carrying of large quantities of stone dust is particularly toilsome, an idea of the practical difficulties to be faced with can be formed.

In spite of these obvious facts the removal of coal dust from mine workings is not — until now — brought into practice with an adequate technique.

8.3.2. The means of removing coal dust

In Poland, as well as in other countries, many appliances have been designed to be used in the removal of coal dust, yet only few of them are in a comparatively wide use.

The most common principle adopted in the mechanical appliances for removing the dust is the suction of the dust analogous to the working principle of the household vacuum cleaner. To make these appliances work more effectively layers of the dust are being raised simultaneously from the surface of the working with nozzles so that the dust could be removed more thoroughly. The appliances in question must have dust filters installed in the containers of the collected dust through which dusts harmful to health cannot pass. Otherwise the removal of coal dust accumulations would pollute the air by the dust fractions < 5 μm. Thus, the problem of filters is one of great importance in the technical solutions of the construction of the appliances in question.

Coal dust can be removed from its accumulations on the surface of workings, or from the air in places at which its densities are high as a result of various technical operations.

In Poland the construction of mechanical appliances for removal of the mine dust from the workings is the business of the Designing and Mechanization Institute of the Coal Mining Industry. These appliances are called dedusters.

Dedusters have many uses: they clean the air of the dust diffused in it (in such cases they are called dust catchers), they remove the deposited coal dust from the surface of workings, they form a part of the dust collection system, and serve occasionally to strew calcium chloride with.

Descriptions are given in the following sections of deduster constructions, designed by the Designing and Mechanization Institute of the Coal Mining Industry which are actually in use in Poland.

8.3.2.1. The GOS injector-type dust collector (Fig. 8.1). This deduster is produced in two variants: GOS-0 and GOS-1.

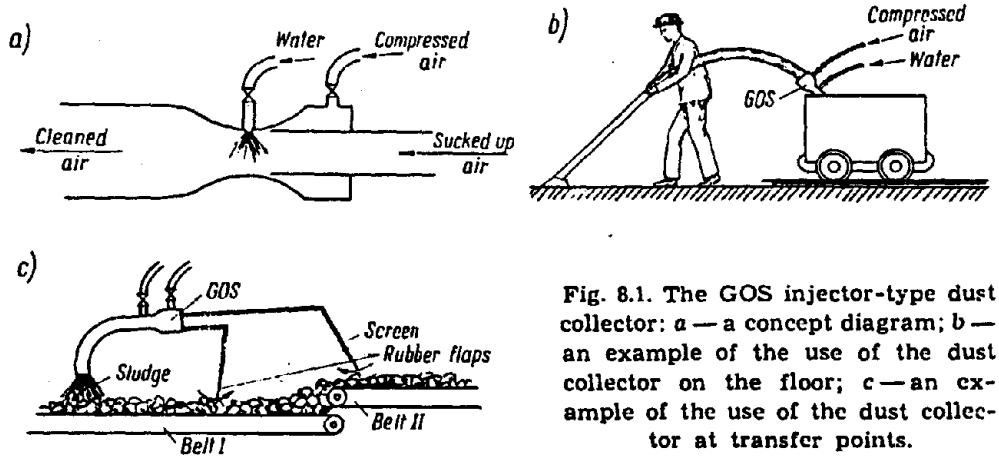


Fig. 8.1. The GOS injector-type dust collector: a — a concept diagram; b — an example of the use of the dust collector on the floor; c — an example of the use of the dust collector at transfer points.

Their technical specifications are as follows:

	GOS-0	GOS-1
Compressed air pressure, kN/sq m	400	400
Dedusting effectiveness, %	99.99	99.84
Compressed air requirement, cu m/min	2.88	7.30
The quantity of sucked-up air, cu m/min	1.17	5.36
Water pressure, kN/sq m	200	200
Water consumption, cu dec/min	5	6

The GOS dust collector is used chiefly to remove dust deposits from the floors of workings (Fig. 8.1b). The deposited dust is sucked through the suction nozzle into the deduster where it loses its dispersibility. The sludge from the deduster is drained into a mining car.

Figure 8.1c shows the way in which the GOS dust collector is used at a belt conveyor transfer point.

8.3.2.2. The GOM-1 wet-type dust collector (Fig. 8.2). The dusty air sucked-in by the fan enters this deduster through the inlet air duct, causing the so-called hydraulic jump. As the result of the intensive turbulence of the water-and-air mixture, the air is cleaned of the dust. The drops of water containing dust are precipitated in the separator. The dust is then collected in a water chamber as mud and from there is removed from time to time.

Technical specification of the GOM-1 deduster:	
Operating efficiency (flow rate of cleaned air), cu m/min	150–200
Power requirement (fan power), kw	15
Resistance of flow, kN/sq m	3.3
Dedusting effectiveness, %	99.7

The GOM-1 deduster is a stationary appliance used in the spatial dusting of shaft bottoms and skip hoist equipment.

In Fig. 8.2*b* an example is given of the use of the GOM deduster for removing the dust from tippers in shaft bottoms.

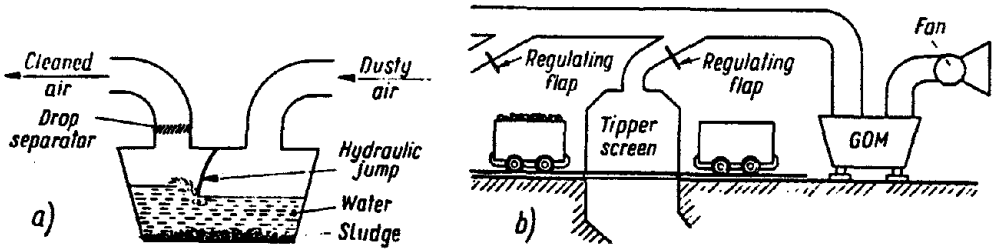


Fig. 8.2. The GOM-1 wet-type hydraulic jump dust collector: *a* — a concept diagram; *b* — an example of the use of the dust collector at tippers in shaft bottoms.

8.3.2.3. Transportable dust collector of the GOP-1 type (Fig. 8.3). This type of deduster is used for removing dust accumulations from various premises such as transformer stations, workshops, locomotive sheds, etc.

Technical specifications of the GOP-1 deduster:

The quantity of sucked-up air, cu m/min	6.5
Fan depression, kN/cu m	15.0
Fan power, kw	4
Weight, kg	140

8.3.2.4. Dust collector *Smok* (Fig. 8.4). Dust collector *Smok* is used for sucking-up the drillings produced in the process of drilling shotholes.

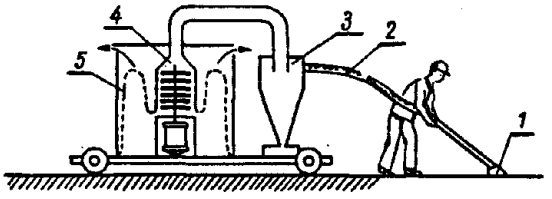


Fig. 8.3. A concept diagram of the transportable dust collector of the GOP-1 type and an example of its use: *1* — suction nozzle; *2* — suction pipe; *3* — dust extractor; *4* — fan; *5* — cloth filter.

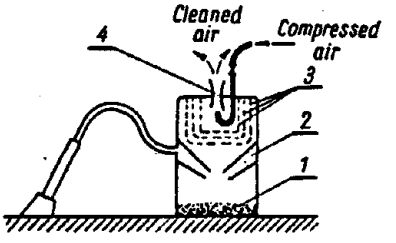


Fig. 8.4. A concept diagram of the dust collector *Smok*: *1* — settling tank for drillings; *2* — cyclone; *3* — cloth filters; *4* — injector driven by compressed air.

It is employed most frequently during the hydraulic drilling in the roof, as the hydraulic drilling of the bore dust is very inconvenient since the

water from the holes pours into the driller's sleeves and gets under his shirt collar, etc. The *Smok* is also used often when holes are drilled in creviced rocks where the hydraulic drilling does not give good results.

Technical specifications of the dust collector *Smok*:

The quantity of compressed air, cu m/min	1.2
Depression, kN/sq m	up to 40
Working efficiency, kg/min:	
coal dust	up to 30
stone dust	up to 50

8.3.2.5. Conveyable gallery dust collector of the OP-1 type (Fig. 8.5). This deduster consists of three rail tubs on which, in a row, are placed: fan *II* with an appliance for raising the dust into the air, the wet-type dust collector GOM, and fan *I* with switches and a system of current carrying wires.

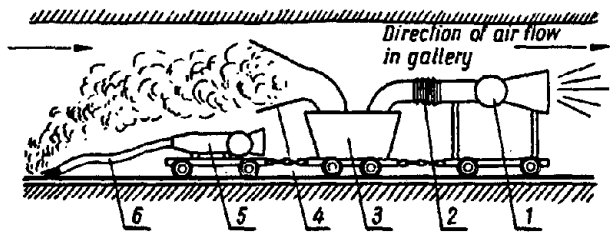


Fig. 8.5. A concept diagram of the conveyable gallery dust collector of the OP-1 type: *1* — fan *I*; *2* — articulated air-dust joint; *3* — GOM; *4* — spatial sucking device; *5* — fan *II*; *6* — pipe for raising up the settled dust.

The air, together with the raised dust, enters through a spatial suction head from the gallery into the wet-type dust collector from which, having been cleaned of the dust, it is let out again through the fan *I* into the gallery.

When a suction head of a different type is attached to this dust collector it can be used for collecting the deposited dust, its action being similar to that of a household vacuum cleaner.

It should be underlined that the above described deduster is, actually, a prototype. The use of it presents serious difficulties. First of all, in the course of the ordinary work of this deduster dangerous clouds of coal dust are being raised to the air. In this way an explosive medium is formed which always creates a serious potential danger. Moreover, inside the hose large static electric charges are formed creating an obvious hazard.

An analogous deduster had been designed much earlier in the Soviet Union [9] and, recently, in Belgium [10]. However, dedusters of this type so far have not been used in mines.

8.4. PREVENTING THE DISPERSIBILITY OF COAL DUST

8.4.1. General information

Coal dust becomes a source of immediate danger when it is raised into the air in the shape of a cloud of a sufficient concentration. A simple conclusion follows: that coal dust deprived of its dispersibility cannot form a dangerous coal dust cloud. Certainly, this is a statement of a general nature since the possibility of raising coal dust into the air and its dispersion in the form of a dangerous cloud depends manifestly upon the energy of the air flow.

For the purpose of investigating this subject special research work were carried out in the *EM Barbara* the results of which were discussed already in Section 3.4.

Water can deprive coal dust of its dispersibility to a varying extent. Actually two basic grades of the loss of its dispersibility by coal dust ought to be discerned here.

Coal dust is considered to be nondispersible if, under the normal manifold conditions of mining operations, it will not drift with the air current. Coal dust, deprived of its dispersibility in the above sense only, is not safe as far as the propagation of explosions is concerned. This was explained in Section 3.4. If, however, coal dust mixed with water shows a consistence making it impossible to be raised into the air and be dispersed even by strong initiators — which has been fully explained in Section 3.4 — then such coal dust is regarded as unable to propagate explosions. Naturally, this coal dust is also a nondispersible dust. But it is much easier to deprive the dust of its dispersibility in the sense of the first general definition — that is, under diverse conditions of mining operations, than to make coal dust unable to propagate explosions.

The question of depriving coal dust of its dispersibility under diverse conditions of mining operations is of a tremendous practical importance because the nondispersible dust, apart from not making mine working dusty, is hoisted to the surface together with the mined coal. The losses resulting from leaving the dust in mine workings are diminished also in this way. Moreover, the lower dispersibility of coal dust is no less important in combating the harmful effects of dust on health. The grains of all kinds of dust in mines measuring less than 5 μm are very harmful to the health of workers as they are the cause of the chronic disease of the lungs known as the anthracosis. Any neglect in preventing the pollution of the air in mines with such dust may cause heavier losses among mine laborers than all accidents taken together. This problem, of tremendous importance to the world mining industry, ought to be discussed sep-

arately in another book, in a very serious manual to be read by all who study mining. Considering what is said above, the employment of all possible methods of preventing the dispersibility of dust is absolutely necessary irrespective of the means adopted for the prevention of the explosibility of coal dust — that is, whether water or stone dust, or any other means, are used for protecting coal dust against explosions.

Coal dust loses its dispersibility at different proportions of free water contained in it; this question was discussed in Section 3.4.2. Dry coal dust, unfortunately, only with difficulty can be wetted with pure water. But it absorbs water easily — that is, it becomes easily saturated with water if it contains a certain percentage of the natural moisture. If the coal in the seam is damp because of a high content in it of free water, then it is technically easy to deprive the dust of its dispersibility. The nondispersibility of dust under diverse conditions of mining operations is a question connected with the velocity of the air flow and with the circumstances in which the dust appears. This question will be discussed in more detail in the following section.

8.4.2. The dispersibility of coal dust under different conditions in mines

Two different possibilities of coal dust being raised into the air ought to be distinguished:

— the raising of the settled coal dust,

— the raising of the coal dust, and making it drift in the air at the time of its formation, or at the time when it already is in the air due to various causes, such as, for example, the transfer of the extracted coal from one belt conveyor to another, the raising of the dust from the gallery floor by feet of passing miners, etc.

The settled coal dust cannot be raised at all by a current of air the velocity of which does not exceed 4 m/sec, this being the maximum air current velocity permitted at places of work. But such dust can be raised as a result of a mechanical movement or by sudden air blows as well as turbulent changes in the movement of the air.

The facility with which settled dust can be raised depends on the following factors:

— the adhesion of the dust to surfaces,
— the cohesion of the dust,
— the viscosity coefficient of the surface layer of the dust,
— the way in which the dust is deposited on surfaces,
— the thickness of the dust layer and the nature of its surface,
— dielectric properties of the dust.

Conditions under which the dust settled in galleries can be raised into the air differ from those existing in longwall workings.

In galleries, in which ventilation currents act on dust deposits for a long time, these deposits become formed in such a way as to create a certain balance between them and the ventilation currents, thanks to which the dust deposits are not raised. When this balance becomes unsettled through a temporary change of any of the factors listed above the raising of the dust will follow and will continue until the new conditions of the balance become stable.

In the conditions existing in mines the most frequent cause of the raising of large quantities of dust deposits is their being mechanically stirred.

In longwall workings, in the course of normal mining operations, the formation of dust deposits undergoes continual changes. Moreover, dust deposits on the walls are very often disturbed mechanically and, therefore, coal dust can be and is raised even by air currents of a lower than the maximum permitted velocity — that is, lower than 4 m/sec.

The velocity of the air in longwall workings depends on the inclination of the walls.

The raising of coal dust is particularly easy in longwall workings in which the decline exceeds 20°. In such conditions might appear gravity loading of coal facilitating the raising of coal dust at very low velocities of the air. When the decline is somewhat smaller and the gravity loading of coal does not appear there is still the crew moving about at their work at the longwall face, and this movement causes the extracted coal to slide down which also greatly facilitates the raising of coal dust.

Coal dust which cannot be raised by the flow of air in the described conditions in mines is considered to be nondispersible.

8.4.3. Requirements with regard to the water used for preventing the dispersibility of coal dust

Water used for spraying coal dust must satisfy the following requirements:

— it must not be unhealthy for people,

— it must not contain suspended matter which causes the clogging of water nozzles commonly used for spraying coal dust with water.

Such water, according to regulations now in force, must satisfy the bacteriological requirements binding with regard to the municipal water. However, this does not seem to be satisfactory since water can be harmful on account of its chemical composition. Even mineral water possessing medicinal properties can be unhealthy for persons who inhale it with the

air in excessive quantities, or else if they are in a daily contact with it during all of the working hours.

Taking into consideration exactly this that the miners breath the air containing atomized water during all their work hours, the requirements with regard to water used for spraying mine workings ought to be formulated more precisely. Yet, in many cases, it is difficult to fulfil the requirements with regard to the usable water, simple as they are in principle. Ordinarily, coal dust is sprayed simply with mine water which, in the majority of cases, does not satisfy the requirements. It is usual to have the water examined chiefly from the bacteriological point of view.

To make the water free of the suspended matter is technically possible with the use of special filters. However, the fulfilment of the requirement that the water should not be harmful because of its content of bacteria and its chemical composition is a much more difficult problem. In many cases it would have been desirable to have drinking water supplied to mines, but this can be connected with serious local difficulties.

8.4.4. Wetting agents

The ability of water to wet coal dust can be distinctly increased by the use of what are called surface-active compounds which, further on, will be called simply the wetting agents. These are substances which, in water solutions or in other solvents, exibit a very characteristic behavior. They lower considerably the interphase voltage which will be referred to later on simply as the surface tension. The lowering of the surface tension of water greatly facilitates the wetting of coal dust with it. The most common wetting agent is the soap of everyday use. Wetting agents act as they do because their particles are of a dipole structure (as those of water) and, therefore, a monomolecular layer of the wetting agent is formed on the surface of water.

Chemically, wetting agents are either ionic or nonionic. As a means of combating the coal dust hazard in mines nonionic wetting agents — that is, the wetting agents which do not dissociate in water, are more effective. The great advantage of these agents is that they retain their dipole structure which means that they do not precipitate from the water solution in the form of salt, when the ions of acids, bases or salts happen to be present in the solution. Another valuable property of such wetting agents is that they are only slightly corrosive. Wetting agents have to fulfil many requirements of which the most important are the following:

— a 0.1 percent solution of the wetting agent in distilled water ought to produce a surface tension lower or at worst not higher than 0.035 N/m (J/sq m);

— a 0.1 percent solution of the wetting agent in water ought to cause the sinking of the *d25 Barbara* coal dust poured over the solution at the rate of at least 3 mg/sec; the concentration of the technologically used wetting agent should not exceed 0.3 percent of the active mass in the water;

— the wetting agent should not increase the explosibility of coal dust;

— the wetting agent should not be detrimental to the human health.

Actually, the requirements in relation to wetting agents go much further than that. There are very many good wetting agents manufactured by the chemical industry the use of which is not allowed in the mining industry because they are harmful to the skin or to the respiratory tracts. Wetting agents are tested very penetratingly by medical specialists before they can be approved for use in the mining industry.

In Poland, the Chief Sanitary Inspector approved for use in the mining industry two wetting agents:

— the ionic wetting agent KBS (sodium kerylbenzene sulfonate),

— the nonionic wetting agent Alfenol 8, a product of condensing ethylene oxide with alkylophenoles.

The critical concentration of the KBS wetting agent — that is, the concentration at which the lowest surface tension is produced of its solution in water, amounts to about 15 percent of the active substance. In such a solution it achieves the reduction of the surface tension of (distilled) water to about 0.03 N/m, the surface tension of distilled water amounting to 0.073 N/m. The KBS wetting agent, being of the ionic type, cannot be used with saline mine waters as this would cause the formation in the solutions of durable insoluble compounds.

The KBS wetting agent is used in a solid or liquid form. In solid form it is manufactured as sticks, the mass of each stick amounting to about 50 g. In this form it is used for the injections of water into the seams. The stick is placed directly in the shothole. The KBS wetting agent in the liquid form, in order to be of the proper consistency, is composed of the following ingredients (in percentages):

KBS	— 20
urea	— 20
sodium sulfate	— 5
water	— 55

For liquid wetting agents there is a good-working wetting-agent proportioner constructed by ZKMPW DZ-1 (The Designing and Mechanization Institute of the Coal Mining Industry — DZ-1).

A certain difficulty in the way of spreading the use of the KBS wetting agent causes the requirement of measuring the wetting agent concen-

tration in the air which should not exceed 100 mg of the active substance per cubic meter of the air. The measurement itself is connected with certain difficulties though ordinarily the concentration of the wetting agent does not exceed the regulation level.

Alfenol 8 as a nonionic wetting agent has better properties than the KBS wetting agent and can be used in salt solutions as well as in hygroscopic pastes containing $CaCl_2$.

The critical concentration of the Alfenol 8 amounts to about 0.05 percent; the reduction of the surface tension of the water solution brings the tension down to 0.03 N/m.

For the sake of accuracy it should be said that the Chief Sanitary Inspector permitted the use of both above mentioned wetting agents in the mining industry under certain conditions, among which the one which ought to be specified is that medical attention has to be provided for workers who are exposed to the risk of coming into contact with the solutions of wetting agents.

The use of wetting agents is being propagated not only for the prevention of the dispersibility of coal dust but also for combating its explosibility and for the suppresion of dusts detrimental to health.

Extensive investigations on the effectiveness of wetting agents were carried out in the *EM Barbara* [116].

Wetting agents are not used on any considerable scale in the coal industry in western countries because — as we are informed — their effectiveness is not up to what had been expected.

8.4.5. The most common places and installations requiring prevention of the dispersibility of coal dust

Coal dust ought to be deprived of its dispersibility at the places where it is formed as well as at such places where it is likely to be raised to the air. This is the general rule. Among the most common places of fighting against the dispersibility of coal dust the following ought to be mentioned:

- the faces where shotfiring is conducted,
- coal cutting machines,
- coal loaders,
- drillers and drilling rigs,
- transfer and discharge points,
- conveyor and car haulage roads,
- dumps,
- skip hoist equipment.

To the most common and most widely used contrivances for depriving dusts of their dispersibility belong spray nozzles.

8.4.6. Spray nozzles

8.4.6.1. General information. Nozzles are used for the purpose of spraying the air with atomized water and of distributing water as evenly as possible over the sprayed surface.

Nozzles can be divided in two principal groups:

— water nozzles to which water only is supplied under pressure,

— hydroaerial nozzles to which are supplied water and compressed air, the latter facilitating the spraying of water especially in the form of fog.

The use of compressed air is being very rapidly and progressively restricted so that water nozzles are of the greatest practical importance. The use of water and air nozzles, in spite of their merits, is diminishing.

Over a long period of time various nozzles were put into use in mines, introduced locally as improvements upon the previously used types, or even as inventions. Thus, it became necessary to carry out systematic tests with the nozzles, the merits of which were proved in practice, in order to select the most effective ones and the easiest to manufacture.

A very extensive work on this subject had been carried out by J. Gruszka of the *EM Barbara*.

On the basis of these tests the Designing and Mechanization Institute of the Coal Mining Industry worked out the construction design of two principal types of spray nozzles, namely, of the conical and flat spray nozzles.

8.4.6.2. Basic information on the work of spray nozzles and on their parameters. On leaving the nozzle water becomes divided into a number of thin jets or into thin layers. These jets leave the nozzle with a high velocity and, consequently, their kinetic energy is considerable. The inert air resistance and friction moderate this velocity and the kinetic energy of the jets gradually declines. This phenomenon causes the disruption of the jets at first producing large drops of water and then progressively smaller and smaller drops until they turn into a fog depending on the kinetic energy reserve.

The higher is the pressure of water supplied to the nozzle, the higher is the velocity of the water jetted from it and the finer is the spray — that is, the drops of water are the smaller.

Of considerable importance is the construction of the nozzle and its hydrodynamic characteristics resulting from the construction of spray

disks, etc. Spray disks distinctly help the disruption of the water jets by the influence of the centrifugal force and they increase the jet velocity.

With every nozzle the following three zones can be distinguished (Fig. 8.6).

— the zone of continuous jets, *a*
— the zone of drops, *b*
— the zone of fog, c.

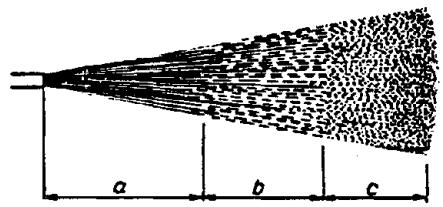


Fig. 8.6. Basic zones in the spray of water leaving the nozzle: *a* — the zone of continuous jets; *b* — the zone of drops; *c* — the zone of fog.

When the shape of the figure created by the water jetted from the nozzle is considered the nozzles are classified as:

— conical with a circular base, Fig. 8.7*a*,
— conical with a triangular base, Fig. 8.7*b*,
— conical with a tetragonal base, Fig. 8.7c,
— flat with an elliptic base (fan nozzles), Fig. 8.7*d*.

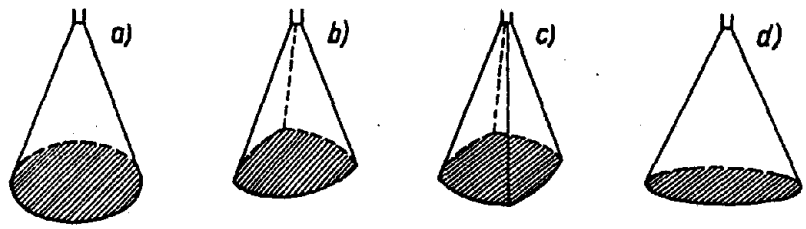


Fig. 8.7. The types of nozzles according to the shape of the figure created by the water jetted from the nozzle: *a* — circular; *b* — triangular; *c* — tetragonal; *d* — flat.

From the viewpoint of the distribution of water on the sprayed surface nozzles are divided into groups as follows:

— producing a full cone, Fig. 8.8*a*,
— producing an empty cone, Fig. 8.8*b*,
— producing a partially filled cone, Fig. 8.8c.

Spray nozzles are characterized by the following parameters:

— the angular field of the cone α,
— the effective range of the nozzle, l,

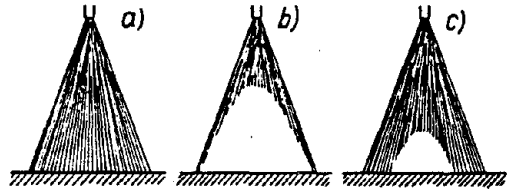


Fig. 8.8. The types of nozzles according to the distribution of water on the sprayed surface: *a* — producing a full cone; *b* — producing an empty cone; *c* — producing a partially filled cone.

— the uniformity of water distribution over a unit of the sprayed surface,

— the working capacity.

The first three parameters are illustrated by Fig. 8.9.

The working capacity is expressed in terms of the relation between the pressure (N/sq m) of water supplied to the nozzle and its productivity (cu dec/min).

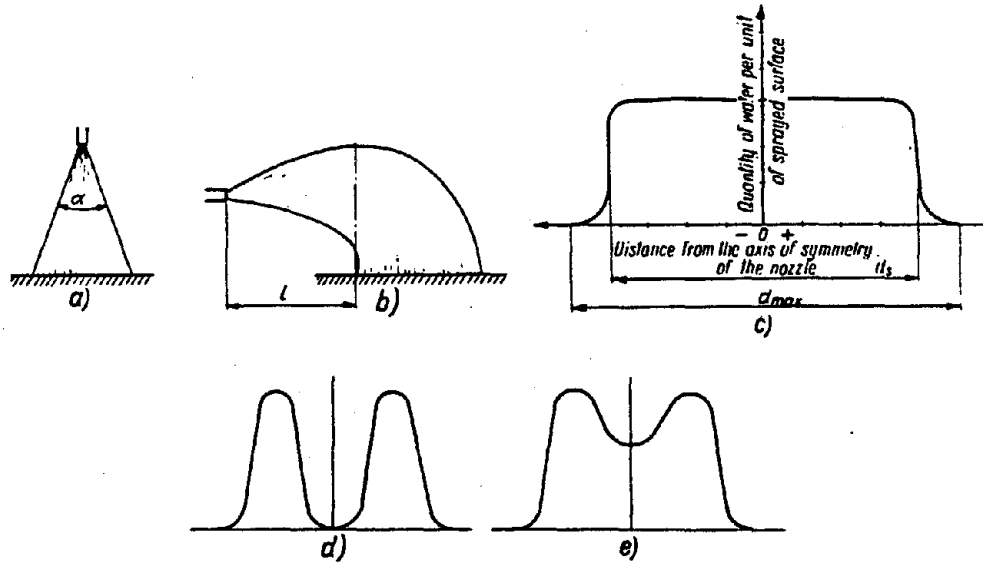


Fig. 8.9. The basic parameters of spray nozzle: *a* — angular field of cone; *b* — effective range of nozzle; *c* — fall of water per unit of sprayed surface; a graph expressing this with reference to the nozzle producing a full cone; *d* — a graph expressing the same with reference to the nozzle producing an empty cone; *e* — a graph expressing the same with reference to the nozzle producing a partially filled cone.

8.4.6.3. The construction of the Polish spray nozzles and their working capacity. Figure 8.10 shows cross sections, of the conic and flat spray nozzles and in Fig. 8.11 diagrams are given illustrating the productivity

of the actually used spray nozzles depending on the water pressure. All productivity curves represent mean results of very careful investigations. The diagrams make it possible to estimate the minimum water pressure necessary to an adequately effective operation of spray nozzles.

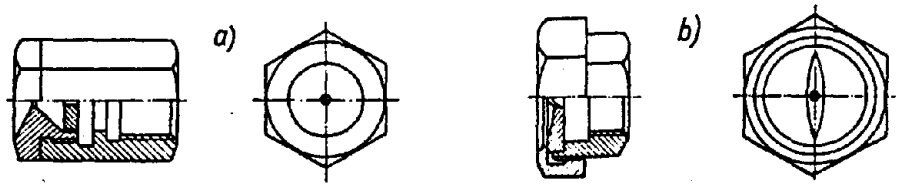


Fig. 8.10. Spray nozzles: a — conical *DS*; b — flat *DP*.

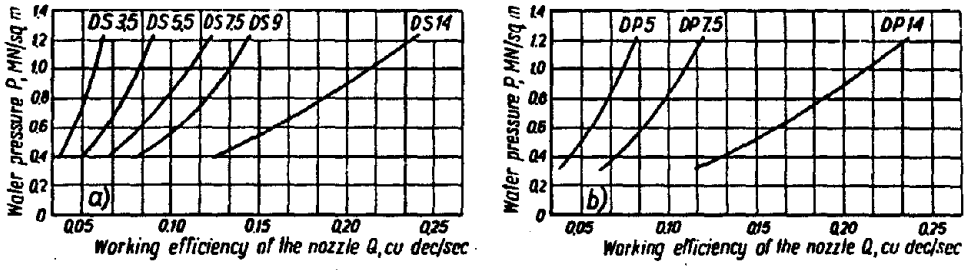


Fig. 8.11. Graphs showing the working efficiencies of Polish spray nozzles actually in use as depending on the pressure of water in water pipes: a — for the *DS* nozzles; b — for the *DP* nozzles.

In Table 8.2 technological and operational parameters are scheduled of both types of spray nozzles. The conic nozzles are denoted by the symbol *DS*, the flat nozzles by the symbol *DP*.

Parameters included in Table 8.2 permit to make an appropriate selection for use of a particular type of the spray nozzle. Nevertheless, in order to facilitate the selection, in Table 8.3 are listed the recommended types of spray nozzles for particular tasks. The symbol + in the table indicates that particular type of the spray nozzle is recommended for the work specified, the symbol — that the nozzle is not recommended, and the symbol ± that the nozzle can be used if necessary.

The proper selection of the spray nozzle as well as its location are of great importance. First of all spray nozzles should be so placed as to reduce to the minimum the risk of sprinkling with water any person working in the vicinity. When this elementary rule is not observed the vexed worker will close the valve, especially in the absence of supervisors, and the spray simply will cease to function.

8.4.6.4. Hydroaerial spray nozzles. In order to produce a very good mist the water and compressed air (the hydroaerial) spray nozzles are

Table 8.2

Specifications of the Technological Working Parameters of Spray Nozzles

Type	Shape of the jet	Spray cone angle, degrees	Water flow intensity within the range of pressure 4 to 12 kg/sq cm, liters/min	Effective surface of spraying F, sq m	Effective range of the spraying function of nozzle, m
DS 3.5	conical	80–90	2.3–3.7	1.5	2.2–1.8
DS 5.5	conical	90–100	3.1–5.4	1.5	1.5–1.3
DS 7.5	conical	90–95	3.9–7.3	2.0	1.7–1.5
DS 9.0	conical	95–100	4.7–8.7	1.8	1.6–1.5
DS 14.0	conical	90–100	7.5–14.2	2.0	1.8–1.5
DP 5.0	flat	90–100	2.7–5.0	0.7	2.5–2.0
DP 7.5	flat	110–120	4.3–7.3	0.8	2.3–2.0
DP 14.0	flat	110–120	8.0–14.3	1.0	2.0–1.7

Table 8.3

Recommended Scope of the Use of Spray Nozzles *DS* and *DP*

Workplace	Type of the nozzles							
	DS 3.5	*DS* 5.5	*DS* 7.5	*DS* 9.0	*DS* 14.0	*DP* 5.0	*DP* 7.5	*DP* 14.0
Spraying of the deposited dust	—	±	±	+	+	—	—	±
Precipitation of the airborne dust	—	—	—	±	+	±	+	+
Discharge and transfer points	+	+	+	+	+	—	—	±
Spraying the cars with output	—	—	+	+	+	—	—	±
Spraying the workplaces of mining machinery (combined cutter loaders, cutters)	—	—	—	±	+	±	+	+
Spraying the winnings, the sidewalls and the roof of workings	—	±	±	+	+	—	+	+
Special uses	+	+	+	+	+	+	+	+

used. There are many different constructions of such spray nozzles utilizing compressed air for atomizing water either inside the spray nozzle, or directly it leaves the nozzle.

In Fig. 8.12 a schematic representation is given of the construction of the spray nozzle in which compressed air atomizes the water inside the nozzle, and the construction of the nozzle with which water is atomized as it leaves the nozzle.

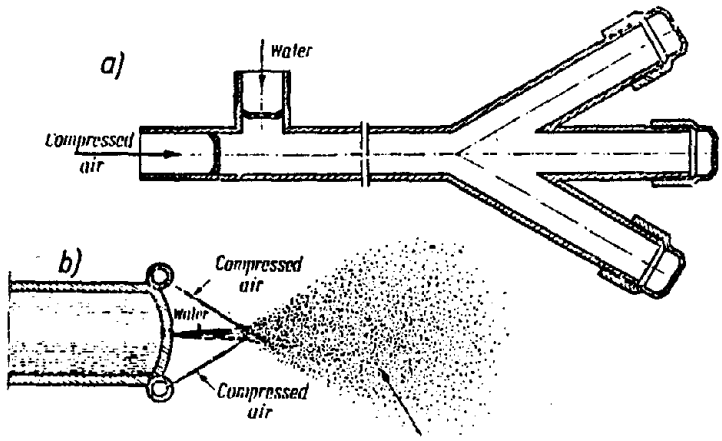


Fig. 8.12. A schematic diagram of the hydroaerial spray nozzle: a — water is atomized inside the nozzle (a foreign construction); b — water is atomized at the outlet of the nozzle (constructed in the *Zabrze* mine).

Hydroaerial spray nozzles disperse water better than water spray nozzles and they are particularly useful before shotfiring when they fulfil a double function: they reduce the dustiness of the air, and contribute to the more rapid reduction of the concentration of nitric oxides after shotfiring. Apart from that, the dispersion of water makes shotfiring much safer in the presence of firedamp and coal dust. By this simple means weak ignitions of firedamp are effectively liquidated.

Unfortunately, the use of the hydroaerial spray nozzles is very limited now since the employment of compressed air in mines is being reduced out of economical considerations.

Hydroaerial spray nozzles can constitute a certain danger in cases of the clogging of water supply by impurities. In such cases compressed air raises the dust to the air. To avoid such hazards hydroaerial spray nozzles should be furnished with an automatic blocking system to shut off the supply of compressed air when the supply of water fails.

Very essential are reports concerning the feelings of comfort or discomfort of men, as well as concerning the visibility, depending upon the quantity of atomized water in the air. According to investigations carried out in the *EM Barbara* [86] up to the content in the air of 50 g of water mist per cubic meter men are able to abide in a given place though — with a concentration approaching 50 g/cu m — a longer stay becomes very

unpleasant to a human being; but the visibility is not too bad. When the concentration of the water mist in the air amounts to between 50 and 150 g/cu m to stay in the place becomes so uncomfortable that men are not able to work in such conditions, visibility is very limited; from the distance of 1 m only the rim of the Rc12 cap lamp can be seen. When the contents of water mist amounts to anything between 150 and 300 g/cu m it is practically quite impossible to remain in the given place as the clothes become wet through after a short time. Visibility is so limited that, from the distance of 1 m, it is impossible to distinguish the kind of a miner's lamp.

On the basis of the above informative data it is possible to estimate whether the content of the wetting agent per cubic meter of air does not exceed the norm of 100 mg fixed by the Chief Sanitary Inspector. If the norm were exceeded conditions would become quite unbearable for men on account of the excessively large quantities of water atomized in the form of the mist in the air when one assumes that the concentration of the wetting agent in water is normal.

8.4.6.5. Preventing the dispersibility of coal dust when combined cutter loaders are being used. When coal cutters and coal loaders are used great quantities of dispersible coal dust are produced. The title of this section refers to combined cutter loaders because these machines produce particularly great quantities of dispersible dust thereby creating a very serious problem for the world mining industry.

According to data from the countries in which the coal industry is most developed [120] the quantities of small coal produced when combined cutter loaders are used amount to:

— fractions < 0.5 mm — 5 to 17%,

— fractions between 0.5 and 10 mm — 23 to 45%.

As a result, in the neighborhood of combined cutter loaders, and generally in the air passing through the places where these machines work, the concentrations of the dust harmful to human health — that is, the grains of which are < 5 μm, highly exceed all the maxima permissible in the world. The great dustiness of the air in the vicinity of these machines is so manifest that, at a distance of very few meters from the combined cutter loaders at work, the visibility is none unless measures are taken to prevent the dispersibility of coal dust. The problem of the health-impairing effects of the dust produced by combined cutter loaders belongs to foremost problems facing the world mining industry and, so far, it was not solved in a satisfactory way in any country.

Naturally, combined cutter loaders produce also tremendous quantities of explosive coal dust carried by the air current.

The most proper method of combating the dispersibility of coal dust

is that of infusing water into the coal massif. This method will be discussed in the next chapter.

But the infusion of water into the seams will not suffice by itself. It is only when the seam is naturally damp, and in a very high degree at that, the dispersible coal dust will not be produced by the work of the combined cutter loader.

Beside the infusion of water into the coal massif the basic means of reducing the dispersibility of the dust is the supply of atomized water close to the spot at which the coal is crushed by the cutting elements of the machine. The internal and external spraying with water is the method employed to this end.

The internal spraying consists in the supply of water to the cutting aggregate of the machine. The water sprays the cutter blades. For the external spraying, water spray nozzles are used or sets of such nozzles directing the atomized water toward the cutting aggregate.

The entire spraying installation must be very carefully constructed by the manufacturing plant. Only such installations should be admitted to use, the efficient work of which had been tested. Spray installations one sees from time to time modified or designed by the miners themselves are, for the most part, not sufficiently effective.

In order to improve summarily the effectiveness of the fight against the dustiness produced through the work of combined cutter loaders work is carried out with the use of the dust-collecting equipment, foam-producing equipment and new constructions of the cutting aggregates. Likewise, the use of additional guards on the combined cutter loaders gives good results in protecting the workers operating the machines against the cloud of coal dust; such guards reduce also the dispersibility of the dust.

What is said above refers equally to the prevention of the dispersibility of dust when coal cutting machines are at work.

8.4.7. Infusion of water into the coal massif

8.4.7.1. General information. In Section 8.4.3 we discussed the use of water for reducing the dispersibility of the already produced dispersible coal dust particularly at the places where it can be raised to the air. The method of infusing water into the coal massif is presented in a separate chapter on account of the fact that it consists in making the coal so damp as to prevent the dust produced from it to be raised to the air under the normal working conditions existing in mines — that is, when the drilling, cutting and similar operations are in progress.

Coal contains always the hygroscopic as well as free water. The con-

tent of free water in the seam is a matter of great importance to the problems of the explosibility of coal dust since it exerts a great influence on the dispersibility of coal dust. Apart from that free water reduces the ignitability of coal dust.

The content of the hygroscopic water in Polish bituminous coals oscillates between 0.3 and 10 percent and, on the average, amounts to 3.8 percent.

The total water content — that is, the sum of the hygroscopic and free water, oscillates between 5 and 23 percent and amounts to 7.5 percent on the average.

The content of free water oscillates between 0.5 and 15 percent and amounts to about 3.7 percent on the average. If the content of free water exceeds considerably 2 percent the coal dust produced during mining operations is nondispersible. In particular, if the coal in the seam contains such quantities of water in the fissures that it oozes out when shotholes are drilled the coal dust produced in the winning of coal is, under normal conditions, entirely nondispersible.

According to investigations carried out in the Central Mining Institute [109] the dispersibility of coal dust depends on the total content of water — that is, on the sum of the hygroscopic and free water. This dependence is expressed by the following empirical formula giving a general orientation in this matter

$$W_c = 1.83\,W_h + 2.2 \tag{8.1}$$

where

W_c — is the total content of water in coal, %,

W_h — is the content of the hygroscopic water, %.

When $W_c > 1.38\ W_h + 2.2$ the coal does not produce dispersible dust in the process of being mined.

It is necessary to underline that the above formula merely gives an orientation in the matter.

According to information found in the literature on the subject coal does not yield dispersible dust in the process of being mined when the total content of water amounts to about 8 percent or more.

The conditions of Polish coal fields are such that, in the considerable majority of cases, coal produces a dispersible coal dust in the process of mining. Therefore, on account of the health-harming effects of the dust and in order to suppress the explosibility of coal dust the infusion of water into the coal massif is strongly indicated. A uniform saturation with water of the coal substance is impossible because the water enters only the fissures.

Very interesting basic investigations on the penetration of the infused water into coal seams had been carried out at *Cerchar* [16]. These investi-

gations proved that, since water enters most easily large fissures, the biggest quantity of water flows through fissures larger that 100 μm with the result that whole zones of smaller fissures are not filled with water. Water does not enter fissures measuring several micrometers. The infusion of water is the most effective when the coal contains an extensive network of fissures to which water enters.

Apart from the size of the fissures and the closeness of the network they form, in the phenomenon of the infusion of water into a seam of considerable importance is the petrographic composition of the coal. Small strips of fusain can absorb 6 to 7 percent of water. Vitrain on the other hand, is impermeable to water which can only fill the fissures and these do not occupy more space than 1 percent of the vitrain volume.

Investigations on the influence of the quantity of infused water upon the dispersibility of the dust, carried out for the sake of orientation, indicated that over a certain content of free water further infusion of water becomes ineffective. According to tentative investigations at *Cerchar* this limit content of free water amounted to about 4 percent.

It follows from the above general information that the presence of larger fissures, through which water flows freely, is undesirable since it prevents the water from entering the network of smaller fissures.

The water pressure necessary for the infusion of water into the coal massif depends on the structure of the coal — that is, on the size of fissures and the denseness of their network, as well as on the petrographic composition of the coal.

By using rather high pressures for the infusion of water the fissures, into which water could not enter under lower pressures, can be caused to widen and, in consequence, the desired effect is obtained. A serious role can also be played by the time taken for infusing the water. In the considerable majority of cases, however, it is practically impossible to let the time factor play its role since — in the mining practice — there is, as a rule, little time for the infusion of water. This operation must be comprised within the organizational work cycle.

The method of infusing water into the coal massif had been introduced originally for the prevention of the health-harming effects of dusts < 5 μm, namely, by reducing the concentration of such dusts in the air. The employment of this method was readily accepted in the mines as it had a distinct influence on the gettability of coal. This phenomenon results from the destruction of the cohesion of the coal through the water infused under pressure into the fissures. For example, a hard coal which could not be exploited with a combined cutter loader without previous undercutting operations became gettable after the infusion of water into the coal massif. A very common effect of the infusion of water into the seam

is the considerable facilitation of the winning of coal by shotfiring resulting in the reduction of the quantity of explosives used per ton of the output. Moreover, the infusion of water into the coal massif influences very favorably the yield of coarser sizes.

There are four basic systems of the infusion of water into the coal massif:

— the infusion of water by short holes,
— the infusion of water by long holes perpendicular to the wall face,
— the infusion of water by long holes parallel to the wall face,
— the infusion of water before the development of the seam.

8.4.7.2. Infusion of water by short holes. This system consists in the infusion of water through holes from 1.5 to 3 m long, perpendicular to the face of the wall. The distance between the holes in most cases is between 1.5 and 6 m. Each infusion, as a rule, includes one web and must be repeated daily.

With this oldest system the process of the infusion of water is applied in zones where shifts are numerous and, consequently, the process consists in washing the fissures thereby making the water act on the dust contained in these fissures. Besides, water pours out through the larger fissures in the face of the wall so that the effect of the infusion of water is still far from being uniform. With modern systems of the organization of work at the walls for the consecutive operations of the infusion of water into holes no room can be found in the work cycle, particularly when combined cutter loaders and advancing support are used; in Great Britain, for instance, these were exactly the reasons why the infusion of water into seams, widely in use until quite recently, is now almost entirely relinquished.

8.4.7.3. Infusion of water by long holes perpendicular to the wall face. This system is, in principle, similar to the one described above except that the length of the holes amounts to from 8 to 15 m and the distance between the holes to about 1.5 times the length of the hole. Consequently, each infusion includes several webs and the infused water penetrates beyond the zone affected by the maximum exploitation pressure — that is, to the formation containing no large fissures. Thus, the distribution of water in the coal massif is more uniform. For this system room can be found in the organizational schedule of the work at the wall since the infusion is done periodically, for example, during hydraulic filling or on holidays.

In the mines of the Lower Silesian Association of the Coal Industry the system [155] of infusing water through holes 4 m long was introduced. Figure 8.13 gives a diagrammatic illustration of the above system. The drilling of holes for the infusion of water is related to the advance of the

wall, and the length of the holes is selected so as to make every new hole comprise in its reach three daily advances of the wall. In this way the number of holes drilled daily is reduced to the minimum and the required distance between the holes is kept, namely, $\frac{d}{4}$ where d represents the distance between the holes drilled on the same day. According to Fig. 8.13 during four consecutive days only the holes marked by figures from *1* to 4 are drilled. On the fifth day the drilling cycle begins anew.

This system is particularly suitable when the daily wall advances are insignificant amounting to about 1 m.

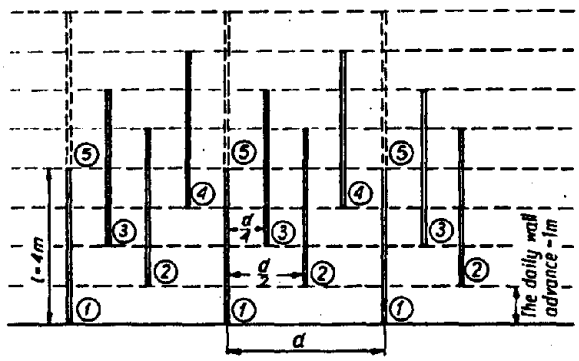


Fig. 8.13. A diagram of the cyclic method of drilling holes for the infusion of water employed in mines of the Lower Silesian Association of the Coal Industry.

8.4.7.4. Infusion of water by long holes parallel to the wall face. From a gallery running above or under the wall, holes are drilled parallel to the wall face. At longer distances from the wall face, water is infused into the coal massif undisturbed by the exploitation pressure which permits a uniform saturation of the massif with water. This system is not organizationally linked with the work at the wall. The infusion of water by means of explosive charges, distributed lengthwise in the holes on a detonating fuse, is very effectively applied here.

Despite the great merits of this system it is seldom used on account of the difficulty in keeping the proper direction when long holes are drilled.

8.4.7.5. Infusion of water before the development of the seam. From mine workings, situated outside of the seam, holes are drilled through the gangue into the not yet accessible seam and water is infused by these holes. So far, this system was not made use of in practice since it is still in the stage of trials.

8.4.7.6. The equipment used for infusing water into the seam. The equipment used for infusing water into the coal massif consists of: a pump, a hose, and a device for packing the hole (a packing head). The technical

specifications of the equipment depend on the magnitudes of pressures necessary to the effective realization of the infusion of water. There are various types of pumps manufactured for this purpose; the discussion of their constructional details is beyond the framework of this book.

The required working pressure depends first of all on the properties of the coal and oscillates between several and about 20 MN/sq m.

When the coal absorbs water even at a very low pressure the infusion of water into the coal massif is obviously greatly facilitated and, often, the employment of pumps becomes superfluous, the hydrostatic pressure of the pipe conduits being sufficient. Exactly this situation actually exists in the mines of the Lower Silesian Coal Basin in which the method discussed here is most frequently and widely employed.

The hard Upper Silesian coals require much higher pressures for the effective infusion of water. For a long time this fact impeded the introduction of the discussed method since no suitable equipment had been available. These difficulties were surmounted and now the pumps designed by the Designing and Mechanization Institute of the Coal Mining Industry and the high-pressure hoses serve their purpose quite well.

The technical specifications of the aggregates for the infusion of water:

NW-1:	
delivery of the pump, cu dec/min	30
working pressure, MN/sq m	~ 15
NW-2:	
delivery of the pump, cu dec/min	20
working pressure, MN/sq m	~ 22
NW-3:	
delivery of the pump, cu dec/min	30
working pressure, MN/sq m	~ 30

For packing the holes the hoses are provided with automatic packing heads shown in Fig. 8.14 in which the broken lines denote the boundaries to which the normal tube covers of the packing heads can expand.

Shotfiring under the pressure of water is more effective than the use of pumps as the means of infusing water into seams. This method, originated in Great Britain, was developed in Poland. The explosive used in this method had been elaborated in the *EM Barbara* and is called *Barbaryt* (permitted nitroglycerine explosive B). The explosive in question requires no protective envelope; it can be introduced direct to the shothole [164].

When a small quantity of the explosive is introduced into a shothole what is achieved is the infusion of water into the seam as was the practice in France. With larger quantities of the explosive the coal is being normally mined. This method of mining distinctly increases the yield of

coarser sizes; the increase in question can be even as big as 20 percent, approximately.

It must be stated that this method cannot be employed under all kinds of conditions; it does not suit extreme conditions. When the coal is highly fissured the water supplied to the hole pours out very quickly and the pressure has no chance to pile up in the hole. The fissures are not filled with water and, generally, the shotfiring is, as it were, wasted having not produced the desired effect. Moreover, the conditions of the shotfiring are not sufficiently safe in the presence of methane. Equally, when the coal is not sufficiently fissured the desired effect also cannot be attained because during the shotfiring there is no water in the network of fissures. Besides, the packing head of the hose can be thrown out of the hole.

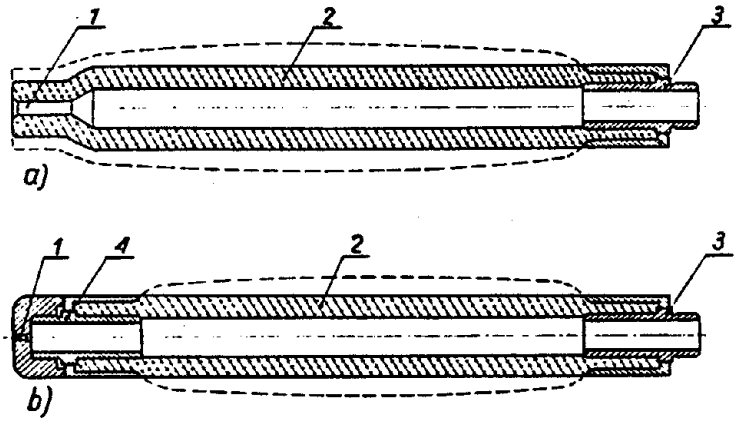


Fig. 8.14. Infusion tube in which sealing is effected by hydraulic pressure: *a* — the head with the expanding outlet; *b* — the head with a stable outlet; *1* — the outlet; *2* — the expanding hose; *3* — the connection; *4* — the ferrule.

The pressure prevailing inside the hole during the inflow of water is the practical measure of the degree to which coal is fissured.

Investigations carried out in the *EM Barbara* have shown that, to employ effectively the discussed method, it is necessary to have the pressure of water in the hole during its inflow amount to anything between 20 kN/sq m and a pressure lower by about 1 MN/sq m than the pressure prevailing in the installation. The magnitude of the pressure of water inside the hole can be determined experimentally with the aid of a special probe shown in Fig. 8.15 [87]. On the basis of the experimental measurement of the water pressure in the hole it is possible to ascertain, with a considerable certitude, whether in the given conditions the method of shotfiring under the pressure of water will be effective.

The method of firing a permitted explosive under the pressure of water is particularly suitable for employment in very dangerous methane

conditions this being safer than the ordinary way of using a permitted explosive on account of the additional safety provided by the water environment surrounding the charge of the explosive.

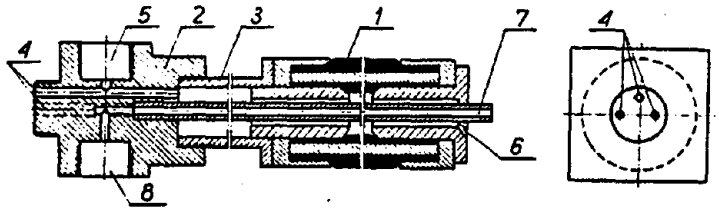


Fig. 8.15. A probe for determining, by measuring the pressure of water, the feasibility of employing the shotfiring method of the infusion of water into seams (after Gruszka and Pawlak): *1* — the expanding hose (the packing of the hole); *2* — the body of the head; *3* — the distance pipe; *4* — the channels through which water is supplied; *5* — the manometer seat; *6* — the calibrated outflow nozzle; *7* — the pressure measuring pipe; *8* — the manometer seat.

8.5. PREVENTING THE DANGER OF THE IGNITION OF COAL DUST

8.5.1. General information

In foregoing chapters we discussed the first line of defense against the danger of coal dust explosions — that is, the prevention of the possibility of the formation of a dangerous cloud of coal dust. All of the discussed methods are of great importance to the problem of combating coal dust, yet the tremendous number of mine workings with a diversity of their conditions makes it impossible to regard this first line of defense as sufficient for preventing the danger of coal dust explosions. The employment of the discussed methods notwithstanding, it is necessary to take into account the possibility of the formation of a dangerous coal dust cloud and of its ignition in view of which the second line of defense has to be organized consisting in the prevention of the initiation of a coal dust explosion.

The following two ways of preventing the initiation of an explosion can be distinguished:

— the first consists in making coal dust difficult to ignite at places where the ignition is possible,

— the second concerns the thermic factors which, in the conditions prevailing in mines, can most easily cause the ignition of coal dust.

8.5.2. Reduction of the ignitability of coal dust

There are many means which can be used to reduce the ignitability of coal dust. Actually, however, only two methods are employed for pre-

venting the initiation of an explosion: the spraying of coal dust, or the dusting of the mine faces with stone dust.

These methods are employed, as a rule, at mine faces at which shotfiring operations are conducted.

The spraying of the faces before shotfiring serves its practical purpose only when it is done in a correct manner.

On account of the fact that the most dangerous deposits of dust are those accumulated in the upper parts of a working, because they are most easily raised into the air by a blast, they ought to be washed down to the floor by a stream of water. If the coal dust is dry it does not lose its dispersibility through the action of water. In such cases it is advisable to employ air-and-water or water nozzles which should be set into action before the shotfiring starts. Atomized water at the mine face makes distinctly more difficult not only the ignition of coal dust but also the ignition of firedamp.

According to investigations made in the *EM Barbara* [68], under conditions of a very strong methane hazard, the yield of the nozzles should amount at least to 30 cu dec/min/sq m. The employment of this method helps, moreover, to reduce the content of the health-harming dust in the air.

The spraying of the mine faces before shotfiring is considerably more effective when a wetting agent is added to water.

The dusting of mine faces with stone dust before shotfiring has been in use in Polish mines since long ago. Yet this method is not worthy of a recommendation. Leaving aside the question of the economic loss through the admixture of incombustible matter to the output of coal, stone dust does not make the ignition of coal dust difficult in a sufficient measure to justify its use. Investigations carried out in the *EM Barbara* proved [69] that, in order to make impossible the ignition of fine coal dust by firing a charge of the blasting powder, the coal dust must contain from 77.5 to 85 percent of incombustible matter. These are very high values. To obtain such values very large quantities of stone dust are required. Besides, stone dust — even when it satisfies the regulation requirements — cannot be regarded as entirely harmelss to human health. After the shotfiring dust grains below 5 μm persist to float in the air for a long time and are inhaled by miners engaged at the face.

The essential protection against the ignition of coal dust by shotfiring is provided by the degree of the safety of the explosive used in the presence of coal dust. The permitted and coal mining explosives are safe in a very high degree in the presence of coal dust. This is evidenced by the fact that in the coal mines in Poland not a single direct ignition of coal dust has been registered by a permitted or a coal mining explosive [69].

8.5.3. The prevention of the initiation of coal dust explosions by explosions of methane

An explosion of methane is the classical initiator of a coal dust explosion. This problem, as well as the most common factors which can cause the ignition of methane, were discussed in Sections 5.1 to 5.5. The information contained there provide also the foundations on which to base the fight against the ignition of methane.

The basic ways of fighting against this danger are: the ventilation, and the control of methane concentrations in the air of the mine. Both of these basic ways represent problems outside of the scope of this book; they constitute great departments of the science of mining.

Yet it is necessary to emphasize very strongly the fact that a proper ventilation of workings and a highly effective control of methane concentrations play the fundamental role in suppressing the danger of coal dust explosions. As a reminder reference ought to be made to Sections 5.2 and 5.4 in which information was given as to how inconsiderable accumulations of methane can initiate a coal dust explosion.

8.6. PREVENTING THE DANGER OF THE PROPAGATION OF COAL DUST EXPLOSIONS BY MEANS OF SPRAYING WITH WATER

8.6.1. General information

Preventing the initiation of coal dust explosions, in spite of a great progress achieved in this field, in the present state of science and technology cannot provide an adequate protection against coal dust explosions. This is evidenced by the explosions of coal dust still occurring in the world mining industry. Therefore, it must be always assumed that there is a possibility of the initiation of a coal dust explosion. Thus, since long ago the next — that is, the third line of defense is in use and it consists in making coal dust unable to propagate an already initiated explosion.

The oldest method employed to this end in the world mining industry is the spraying of coal dust with water. The principles of this method were explained in Sections 3.4 and 8.4. The method is effective only when coal dust, accumulated in mine workings, in its entire bulk becomes saturated with water in such a measure that it cannot be raised to the air and dispersed even by the strongest blast which can possibly occur in a mine.

The spraying of workings with water, as the most generally used basic method of fighting against coal dust in mines, had been abandoned almost in all countries directly after the World War I because the statistics of explosion disasters proved the inadequacy of this method. Undoubtedly,

the essential shortcomings of the method were partly responsible for this but in as many cases this responsibility is shared by the defective performance of the spraying.

It was generally considered that the fundamental fault with the spraying is the transitoriness of the effects of this method in consequence of the reduction of the water content in coal dust through the drying influence of the ventilation of workings. This phenomenon is the more manifest, the drier are the workings and the lower is the content of the relative humidity in the air. The above opinion, though correct, is nevertheless somewhat superficial. The essentials concerning the difficulty of making coal dust safe through the application of water were explained in Section 3.4.

In the period of time during which the spraying method was being discarded no careful basic investigations had been undertaken on the influence of water upon the explosibility of coal dust. Such investigations were carried out in the *EM Barbara* after World War II; they were discussed in detail in Section 3.4. These investigations indicated the conditions in which it is possible to rely upon the use of spraying as the means of making coal dust unable to propagate explosions.

Considering that Poland belongs to the very few countries in which regulations approve of the use of water on a large scale as a means of combating the explosibility of coal dust, a justification of this fact is called for.

8.6.2. The reasons for spraying coal dust with water in the Polish mining industry

The ineffectiveness of water as the basic means for fighting against coal dust, mentioned in Section 8.5.1, was due primarily to the fact that it had been difficult to deprive dry coal dust of its dispersibility by the use of water.

As has been explained in Section 3.4 coal dust imbibes well the water added to it provided that it contains a sufficient quantity of the natural free water. In such cases the employment of the method of spraying can be effective. The use of this method becomes even more justified when the working is so humid in its entire cross section that the relative humidity of the air in the working amounts to 90–95 percent.

The investigations described in Section 3.4 proved that even wet and apparently entirely nondispersible coal dust can propagate explosions if very strong initiators are used. The dust of this kind, though seemingly made safe by its natural humidity, can even be very dangerous when there is a possibility of the coming into play of strong initiators, an occurrence

to be expected, as a rule, in methane fields and in the presence of zones containing dry, dangerous coal dust. It is obviously necessary to make such coal dust safe. The application of stone dust to this end falls short of expectations (this will be discussed in the next chapter) so that there remains, as the simplest and most proper method to be employed in such circumstances, the spraying with water until its content becomes sufficient to prevent the propagation of a coal dust explosion.

The above designation is merely a qualitative one. The necessary contents of water in coal dust depend on the basic parameters of this dust. They are given in Sections: 3.4, 8.4 and 8.6 and are also expressed by formulas in Sections 8.10 and 8.11. The formulas in question furnish the possibility of computing the content of water or of stone dust necessary to make coal dust safe.

The humid or wet conditions of mine workings, containing coal dust of a high natural content of free water, to which reference was made before, occur frequently in Polish mines. In consideration of this, the binding regulations in Poland contain provisions for a widespread use of water as a means of making coal dust incapable of propagating explosions. In such cases this method is even recommended as more effective in the described conditions than the dusting with stone dust. In the conditions prevailing in Polish mines in many cases it is possible to fight against the danger of coal dust explosions by systematically spraying with water the whole surface of workings, particularly when mechanized equipment is used.

8.6.3. The effectiveness of the spraying with water of coal dust in order to prevent the propagation of its explosion

Section 3.4 was devoted to investigations on the effectiveness of water in homogenous mixtures with coal dust. It can be stated generally that the section referred to above dealt with the influence of the natural humidity on the lowering of the explosibility of coal dust. The spraying of coal dust with water cannot be regarded as producing effects equivalent to those produced by the natural humidification of coal dust, in its entire bulk, which is observed in the uniform conditions of damp or wet mine workings. When coal dust is sprayed with water the bulk of the coal dust will not become so uniformly saturated with it and, consequently, in the circumstances at any rate it must be less effective. This phenomenon attracted the attention of Taffanel [166] who was the first to carry out investigations on the comparative effectiveness of the influence of water in homogeneous mixtures with coal dust and in the phase of spraying. What Taffanel ascertained can be expressed in a general way by the statement

that the percentage of water, sufficient to make the propagation of a coal dust explosion impossible, was approximately the same as the percentage of stone dust serving the same purpose. The pioneer investigations of Taffanel, however, were distinctly limited.

More thorough investigations on this problem were carried out in the *EM Barbara* [37].

Within the framework of these investigations 244 experiments were made on a large scale. The investigations in question were carried out under the most difficult dispersion conditions on account of the insurmountable experimental difficulties which would have been experienced under conditions of the easiest dispersion, when the spraying with water would wash the dust from the roof bars down to the floor. The *d*85 and *d*25 coal dusts from the *Barbara* seam were used and the 30mPII and 50 cu m CH_4 initiators were applied.

Taking into consideration the fact that coal dusts in mines differ, as a rule, from each other by their contents of incombustible solid matter, investigations were carried out on the dependence of the effectiveness of spraying coal dust upon the content in it of incombustible solid matter. As the next step a precise comparison was made between the effectiveness of water in homogeneous mixtures with coal dust and its effectiveness in the spraying. Also investigations were made on the effectiveness of water when direct initiators were used as these experiments had a great practical importance in view of the previously mentioned spraying of mine faces before shotfiring. The experiments discussed here were carried out in the 200 m experimental underground gallery and a small part of them in the surface gallery [37].

The spraying was done in the manner similar to that adopted in mines. The necessary contents of incombustible solid matter in coal dust were obtained by mixing it with limestone dust.

The results of the investigations on the use of water in the form of spraying are given in Fig. 8.16. The diagram shows four straight lines for the *d*85 and the *d*25 coal dust with the use in both cases of the 30mPII and of the 50 cu m CH_4 initiators, respectively. The straight lines in question were traced by the method of the least squares on the basis of the results of experiments obtained in particular conditions. The equations which express these straight lines have the following forms:

— the straight line *A* (30mPII, the *d*85 dust)

$$W = -0.74\,n + 61 \tag{8.2}$$

— the straight line *B* (50 cu m CH_4, the *d*85 dust)

$$W = -0.714\,n + 51 \tag{8.3}$$

— the straight line C (30mPII, the $d25$ dust)

$$W = -0.666\,n + 46 \tag{8.4}$$

— the straight line D (50 cu m CH_4, the $d25$ dust)

$$W = -0.765\,n + 40 \tag{8.5}$$

Straight lines, presented in Fig. 8.16, can be drawn for the sake of simplicity as parallels which was done in the publication [37].

8.6.4. The comparison between the effectiveness of water when used for spraying and its effectiveness in homogeneous mixtures with coal dust

8.6.4.1. The comparison, as above, when the 30mPII initiator was used. The comparison in question was made on the basis of the results of investigations on the influence of water upon the explosibility of coal dust in homogeneous mixtures [33]. These investigations were described in Section 3.4.

In Fig. 8.17 straight lines A and C from Fig. 8.16 are shown together with the lines E and F expressing the effectiveness of water in homogeneous mixtures with coal dust as depending upon the contents of incumbustible solid matter in the $d85$ and $d25$ coal dusts [33].

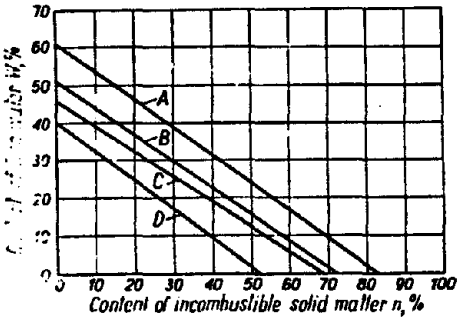


Fig. 8.16

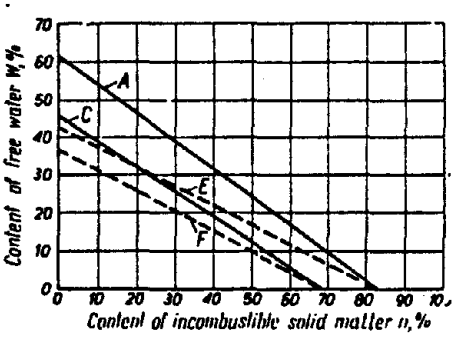


Fig. 8.17

Fig. 8.16. Graphs of the dependence of the percentage contents of water W preventing the propagation of explosions upon the percentage contents of incombustible solid matter n in the heterogeneous mixtures of coal dust with water (the water from spraying); the straight line A — the d85 coal dust, initiator 30mPII; the straight line B — the d85 coal dust, initiator 50 cu m CH_4; the straight line C — the d25 coal dust, initiator 30mPII; the straight line D — the $d25$ coal dust, initiator 50 cu m CH_4.

Fig. 8.17. Graphs of the dependence of the percentage contents of free water W preventing the propagation of explosions upon the percentage contents of incombustible solid matter n in mixtures of coal dust with water (the $d85$ and $d25$ *Barbara* coal dust, initiator 30mPII): the continuous line — water from spraying; the broken line — water in uniform mixtures with coal dust.

The diagram distinctly shows the higher effectiveness of water in homogeneous mixtures with coal dust than when it is used for spraying. For the $d85$ coal dust 1 percent of spray water is equivalent to 1.36 percent of incombustible solid matter, whereas for the $d85$ and $d25$ coal dusts in homogeneous mixtures with water 1 percent of water is equivalent to 1.89 percent of incombustible solid matter. For the $d25$ coal dust 1 percent of spray water is equivalent to 1.5 percent of incombustible solid matter. The difference between the effectiveness of water used for spraying and the effectiveness of water in homogeneous mixtures becomes manifest when the quantities of water, necessary to prevent the propagation of an explosion are computed by a weight unit of pure coal substance.

The effectiveness of the use of water for spraying the dust is denoted by the symbol W_{szc}.

The effectiveness of the use of water for spraying the dust is denoted by the symbol W_{szc}.

The comparative value of the effectiveness of water used in both of the above forms is expressed by

$$\Delta = \frac{W_{szc}}{W_{sjc}}$$

The dependence of W_{szc} and of W_{sjc} upon the content of incombustible solid matter n in coal dust is illustrated in Fig. 8.18. The curves representing the dependence $W_{szc} = f(n)$ for the $d85$ and $d25$ coal dusts are expressed by the following equations:

— the $d85$ coal dust

$$W_{szc} = \frac{-0.74n + 61}{39 - 0.26n} \tag{8.6}$$

— the $d25$ coal dust

$$W_{szc} = \frac{-0.666n + 46}{54 - 0.344n} \tag{8.7}$$

The curves representing the dependence $W_{sjc} = f(n)$ for the $d85$ and $d25$ coal dusts are expressed, on the other hand, by the following equations:

— the $d85$ coal dust

$$W_{sjc} = \frac{-0.527n + 43.5}{56.5 - 0.473n} \tag{8.8}$$

— the $d25$ coal dust

$$W_{sjc} = \frac{-0.527n + 36.5}{63.5 - 0.473n} \tag{8.9}$$

The comparative magnitude Λ of the effectiveness of the use of water in both forms undergoes a reduction as the content of the incombustible solid matter n grows. For the $d85$ coal dust within the range of the value of n from 0 to 70 percent, the value of Δ diminishes from 2.03 to 1.56. For the $d25$ coal dust within the range of the value of n from 0 to 60 percent, the value of Δ diminishes from 1.48 to 1.28.

The dependence of Δ upon n is presented in the graphic form in Fig. 8.19.

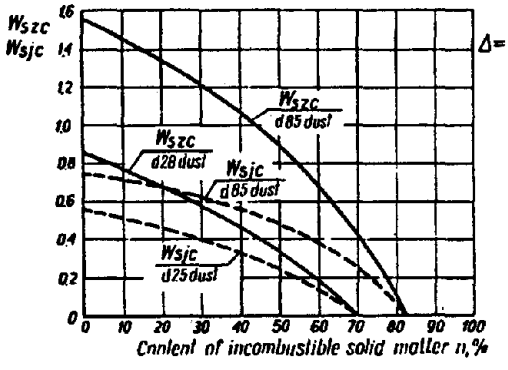


Fig. 8.18

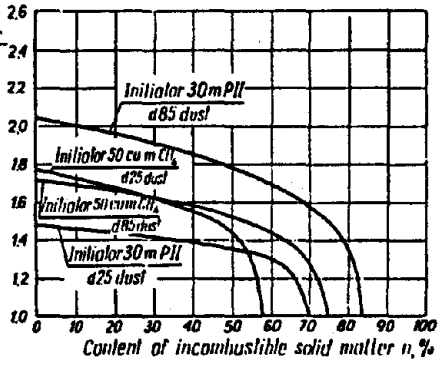


Fig. 8.19

Fig. 8.18. Graphs of the dependence of the effectiveness of spraying with water W_{szc} and of the effectiveness of water in uniform mixtures with coal dust W_{sjc} upon the content of incombustible solid matter n in coal dust (the $d85$ and $d25$ *Barbara* coal dust, initiator 30mPII, the most difficult dispersion conditions). For explanations see Fig. 8.17.

Fig. 8.19. Graphs of the dependence of Δ upon the content of incombustible solid matter n in the mixtures of coal dust with water incapable of propagating explosions (the $d85$ and $d25$ *Barbara* coal dust, initiators 30mPII and 50 cu m CH_4).

8.6.4.2. The comparison when the initiator 50 cu m CH_4 was used. The comparison, analogous to that discussed in Section 8.6.4.1, was carried out with the 50 cu m CH_4 initiator.

In Fig. 8.20 are given diagrams representing the dependence of the percentage content of water W, safeguarding against the propagation of explosions, upon the percentage content of incombustible solid matter n in mixtures of coal dust with water.

No diagrams, analogous to those given in Fig. 8.18, have been included here. Only in Fig. 8.19 the diagrams, representing the dependence of Δ upon n for the initiator 50 cu m CH_4 were given, for the sake of a comparison, along with the curves for the initiator 30mPII. The quickest growth of the effectiveness of water with the increase in the content of incombus-

tible solid matter occurs in the case of the *d*85 coal dust which was discussed in detail in the publication [37].

The course of the curves in the diagram 8.19 is similar for both initiators. The visible differences are caused by the fact that the initiator 30mPII is much stronger than the initiator 50 cu m CH_4.

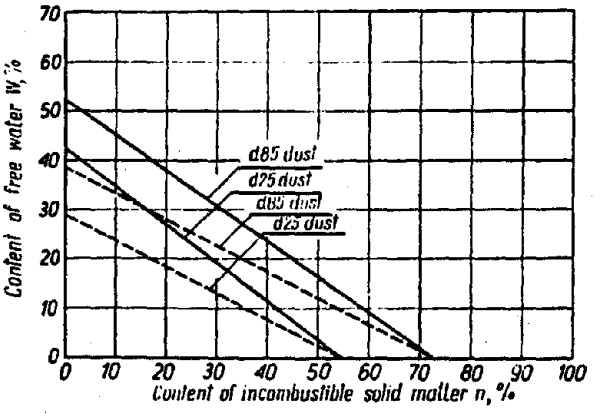


Fig. 8.20. Graphs of the percentage dependence of water W preventing the propagation of explosions upon the percentage content of incombustible solid matter *n* in mixtures of coal dust with water (the *d*85 and *d*25 *Barbara* coal dust, initiator 50 cu m CH_4, the most difficult dispersion conditions). For explanations see Fig. 8.17.

8.6.5. The effectiveness of water when a direct initiator is used

The relevant investigations were carried out for the single purpose of testing the effectiveness of water when used for spraying the mine face before shotfiring. Thus, they were intended to supplement the experiments described in Section 8.5.2. All these experiments were carried out under the most difficult coal dust dispersion conditions.

When a charge of 500 g of the rock explosive Ammonite had been fired it was found that for the *d*25 pure coal dust 10 percent of water sufficed as a safeguard against the propagation of the explosion. On the other hand, in the case of the *d*85 coal dust, 30 percent of water was necessary.

Analogous tests were made with firing a charge of 500 g of black powder from a mortar. It was found that, in order to make the *d*85 pure coal dust incapable of propagating the explosion by spraying the dust with water, 40 percent of water was necessary. When a wetting agent has been added to water the effectiveness of water did not improve perceivably. Water in homogeneous mixtures with coal dust proved to be considerably more effective. It was found that already 10 percent of such water safe-

guard the same kind of dust against propagating an explosion when a charge of 500 g of black powder had been used as the initiator.

8.6.6. The summary of the results of investigations of the effectiveness of water used for spraying

It must be underlined that the described results of the investigations were obtained under the most difficult dispersion conditions. In such conditions it is much easier to impede the development of a coal dust explosion than it would have been in the case of the easiest dispersion. In spite of this, in order to make coal dust incapable of propagating explosions, much larger quantities of water in the sprayed form are necessary than in the form of homogeneous mixtures. Unfortunately it cannot be expressed in a single figure how many times more effective is water in homogeneous mixtures than sprayed water, the value of Δ depending on the explosion initiator, on the degree of the fineness of coal dust, and on the content in it of incombustible solid matter.

Figure 8.19 gives a comparative picture of the value of Δ with reference to two initiators as dependent upon the content of incombustible solid matter n in the dust.

It is worth mentioning that the greatest difference between the effectiveness of the two ways of using water is observed in the case of the d_{85} coal dust with the 30mPII initiator. In these conditions the value of Δ for pure coal dust amounts to 2.03; in other words, the use of water in a homogeneous mixture is approximately twice as effective as it is in spraying. The use of spraying coal dust, even when it is relatively dry, before shotfiring can be effective provided that a strong stream of water will wash down coal dust from the upper parts of the workings to the floor, and the water content in the dust will not be less than 40 percent. One should mention here that in nonmethane fields, when special permitted explosives are used, characterized by a very high degree of safety in the presence of coal dust, neither the spraying with water nor the dusting with stone dust at the mine face are necessary before shortfiring.

8.6.7. General remarks on the spraying of water as a means of preventing the danger of propagation of explosions

As has been mentioned already in the beginning of Section 8.6, according to Polish regulations (amended as this book was being written) the spraying of coal dust with water for preventing it from propagating explosions is approved — that is to say, it is admitted as the basic means

to this end analogously to the dusting with stone dust which will be discussed in Section 8.7. Once more (see Section 3.4) it must be emphasized that this is possible only in such cases when coal dust, in the entire cross section of the working, imbibes water.

The spraying with water of dry coal dust can be applied only locally as, for instance, at mine faces before shotfiring, when the coal is cut and loaded mechanically, etc. (see Section 8.4).

Consequently the decision whether the given dust conditions are suitable for the spraying is of paramount importance.

More than once the wish had been expressed that the minimum percentage of free water in the dust at which the spraying can be effective should simply be made known. Unfortunately, it is not possible to comply exactly with this wish because, as was explained already in Section 4.4, coal dust from different seams is dispersible at different water contents. Apart from this a considerable part is played by the degree of the fineness of coal dust. In consequence mine dusts are capable of imbibing water easily at varying minimum contents of natural free water.

To get an answer to the question concerning the appropriateness of spraying the dust with water the spraying in the given working should be simply tried. As the result of such a trial it is possible to determine whether the entire dust in the working became totally nondispersible through the imbibition of water. Should it be observed that this aim was achieved with regard to the coal dust deposited on the floor, whereas in the upper parts of the workings the dust was not completely deprived of its dispersibility, then — naturally — the spraying with water in this particular working would not be justified.

It must be remembered that, in relatively high workings, it is not at all easy to find out whether on the support, and especially behind the support, certain quantities are not present of a dry coal dust which does not imbibe water.

When it is considered whether in a given working the spraying with water can be applied, particular attention must be paid to the surface layers of dust. If in the working in question the phenomenon of the continuous deposition of coal dust is observed then — even on a wet coal dust — a very thin deposit of a dry, dispersible dust accumulates capable of propagation explosions.

Taking all these factors into account it is necessary to be very cautious in deciding whether, in a particular working, it is advisable to apply the spraying with water as a sure protection against the propagation of explosions.

In spite of the reservations made above concerning the difficulty of determining the limiting percentage content of free water, over which

the spraying of the dust can be applied, the project of new regulations includes a partial provision for exactly this way of determining the applicability of the method of spraying the workings with water.

In nonmethane workings, and in the I category of methane workings the spraying with water is to be permitted simply in such cases when the dust imbibes water.

This should be understood to mean that the imbibing capacity of the dust has to be verified experimentally in the manner described previously. But in seams classified to the II-IV category of the methane hazard the spraying is to be permitted when the contents of free water amount to at least from 15 to 20 percent depending on the category of the methane hazard. The above water contents are high and, indeed, the dust of bituminous coal containing so much water ought to imbibe water practically in all cases. It is intended in this way to create a protection against possible errors in the experimental evaluation of the applicability of the spraying with water under conditions of a serious hazard of explosions existing in seams containing much methane.

It is always very important correctly to collect samples of the dust for determining the content of water. There should be no question here of determining the average value; the samples must be collected in particular from the surface layer of the dust and, at that, in the part of the working where the dust seems to be less humid. On the basis of a great number of experiments mentioned in Sections 3.1–3.4 formulas and nomograms were worked out in the *EM Barbara* which make it possible to compute, through analyzing the basic parameters of the mine dust, the content of water or the content of incombustible solid matter necessary for rendering the given dust incapable of propagating explosions. For computations of this kind the results are needed of the analyses of the basic parameters of the explosibility of coal dust. The formulas and nomograms in question as well as their use will be discussed in Sections 8.10 and 8.11.

It ought to be underlined here that, when there is no good laboratory available and no trained personnel whose knowledge of the problems of coal dust explosions represents a proper level, it is necessary to adopt, as the criterion of the correct employment of the method of spraying, the rule that the content of water in the bulk of the dust in the working should amount to not less than 50 percent. This value is very high; a dust of this kind has the consistency of mud since the quantity of water mentioned above considerably exceeds the imbibing capacity of the dust of bituminous coal.

The water pressure during the spraying must be sufficient to wash the dust by a strong stream from the upper parts of the working so as to bring the entire dust down to the floor. Dust deposits ought to be washed

off the supports of the working and of sidewalls with particular care. This is necessary in order to make sure that coal dust does not remain in places from which it could be raised with ease into the air by a strong blast. Moreover the certitude is gained that even the somewhat drier dust accumulations will be washed down and, lying on the floor, will become better saturated with water.

Having washed the dust from the upper parts of the working down to the floor it is indicated to have the coal dust sprayed with water nozzles over the entire cross section of the working so as to ensure the penetration of water to all places at which the dust might have accumulated.

8.7. THE USE OF DUSTING WITH STONE DUST IN ORDER TO PREVENT THE DEVELOPMENT OF A COAL DUST EXPLOSION

8.7.1. General information

The employment of this method has already been discussed partially in the preceding sections. The principle of its application is very simple. It consists in the admixture to coal dust of such a quantity of incobustible solid matter, generally referred to by the name of stone dust, which will make the dust incapable of propagating an explosion.

The first investigations on the use of stone dust to this end, carried out on a large scale, must be attributed to the French investigator Taffanel cited frequently heretofore.

The effectiveness of stone dust in preventing the development of a coal dust explosion was ascribed to the absorption of heat by stone dust. This, when the content of this dust was sufficient, had been believed to result in preventing the development of the flame in the cloud of the mixture of coal and stone dust. Yet the role of stone dust consists rather in screening the grains of coal dust from the effects of the radiation. Thus, stone dust acts as a screen preventing the transfer of heat through radiation. Partly, the absorption of heat by stone dust also plays a role. But the screening effect mentioned above seems to be the decisive factor. It is very interesting that above a certain degree of the fineness, amounting approximately to 50 percent of fractions < 75 μm, the effectiveness of stone dust does not appear to grow perceptibly.

Lately, American investigators have expressed different opinions concerning the transfer of heat during coal dust explosions, namely [159]:

1. Coal dust clouds cannot be preheated to the ignition temperature by the radiation of the flame alone, when the deflagration velocities are

higher than about 10 m/sec. Consequently, it seems to be improbable that the radiation alone could have caused the transmission of the flame in coal dust clouds up to the detonation velocities.

2. Small molecules in the zone of the radiation of the flame, created by the tar produced and burnt in the process, distinctly increase the degree of preheating.

The explosibility of coal dust depends on a number of parameters which were already discussed. The investigators who carry out their experiments under different conditions obtain different percentages of stone dust contents safeguarding coal dust against explosions. The citing of the results obtained by different investigators is not likely to serve any purpose as their investigations were adapted to the experimental conditions available to them, as well as to the general "policy" deduced from the requirements stated in regulations in force in different countries. The author of the present book intentionally used the word policy because actually, in spite of the existing great hazard of coal dust explosions, the attitude of the coal industry and of the mining authorities to the problem of fighting against this hazard is not quite uniform. Conditions in mines vary considerably so that the requirements concerning the safety of coal dust can be adjusted to suit the average, or the particularly dangerous, situations which occur in the mining practice. Unfortunately, fatal accidents generally happen as the result of the coincidence of particularly unfavorable circumstances. Considering the diversity of conditions existing in mines with incessantly changing and rapidly advancing workings, and the tremendous scale on which mining operations are conducted in developed coal industries, the occurrence of coincidences of unfortunate circumstances cannot be avoided. The regulations, therefore, ought to take into account, first of all, such coincidences of unfavorable circumstances and it is exactly on this point that the policies in different countries show considerable differences. Naturally, to express it in plain words, the expenses connected with the furnishing of the means for preventing the explosibility of coal dust play a great role in this matter. The last mentioned consideration exerts a serious influence on the relevant regulation requirements.

Generally, however, it can be safely asserted that, in almost all countries, is observed a growing stringency in the formulation of requirements pertaining to the prevention of the explosibility of coal dust. This is due not so much to the results of the latest investigations as to the fact that disasters continued to occur despite the observance of the binding regulations. Let it suffice to mention the fact that, when the dusting of workings with stone dust had been introduced, the initially required content of incombustible solid matter in the dust, regarded as safe in respect of the

propagation of explosions, amounted to 50 percent. In Section 6.5, in Table 6.10 contents were given of incombustible solid matter n preventing the propagation of explosions with the estimated probability indices and the limits of the confidence intervals. The values given in the above table are obviously considerably higher than those initially indicated. For, the values of n given in Table 6.10 correspond exactly with the mentioned coincidences of unfavorable circumstances; they were worked out for very strong initiators and for the easiest dispersion conditions. Moreover, they cover the cases of the steady explosions of coal dust and the explosions whose range is 200 m. It is possible indeed to rely on these numbers when the regulation requirements are being fixed.

Speaking about research work carried out in foreign institutes it is necessary, in the first place, to underline their great contribution to the investigations on the problem of coal dust explosions. The results of these investigations helped the author of this book in the course of the work carried out in the *EM Barbara*. The works of foreign investigations are frequently cited in this book.

The role of incombustible solid matter in the explosibility of coal dust was discussed in Sections 3.3, 3.4 and in Chapter 4 dealing with the explosibility of coal dust because the content of incombustible solid matter in coal dust preventing the propagation of an explosion is the measure determining the degree of the explosibility of the given dust.

8.7.2. The kinds of stone dust used and substances increasing the effectiveness of stopping the development of a coal dust explosion

Various kinds of stone dust are added to coal dust to increase its content of incombustible solid matter. The most common of these are limestone dust and clay-slate dust. Apart from the above, on a small scale, the following dusts were also introduced: the gypsum, dolomite and sand dusts as well as the diatomite. Clay-slate dust was used in the past in Poland as well as in other countries but this practice was abandoned on account of the fact that the dust in question has a high content of free silica, very harmful to health.

As stated in Section 3.3.2, according to British investigations, limestone dust was considered to be more effective than the clay-slate dust on account of the fact that calcium carbonate decomposes into carbon dioxide and calcium oxide at a temperature above 800°C. This reaction is an endothermic reaction, therefore it causes the removal of heat from the explosion flame. Apart from this the carbon dioxide, educed in the course of the reaction in quantities amounting to 44 percent, can reduce the explosibility of the system: coal dust — air. Consequently, the assumption

that limestone dust can be more effective than clay-slate dust had its grounds. The remarks cited above, concerning the higher effectiveness of the limestone dust, can be questioned since in the course of investigations conducted by British investigators [150] bicarbonate of sodium, which decompose already at a temperature above 100°C and educes during the decomposition 10.7 percent of H_2O and 52.4 percent of CO_2, did not display the expected effectiveness in impeding the development of coal dust explosions. Nonetheless, British investigators did establish in their tests in a surface experimental gallery, 99 m long of a cross section area measuring 122 cm, that the limestone dust was decidedly more effective than the clay-slate dust. Under the conditions in which the tests were carried out 57.5 percent of limestone dust was found to suffice to stop a coal dust explosion while it was necessary to have 67.5 percent of clay-slate dust to produce the same effect [119].

However the investigations [27] carried out on a large scale in the *EM Barbara* did not confirm the results of the British investigations; on the contrary it was found that the limestone, clay-slate and dolomite dusts are, within the limits of experimental errors, equally effective in making coal dust incapable of propagating explosions. It ought to be stated that this was established as the outcome of 492 experiments. Moreover, in the course of further investigations the equivalence of the clay-slate and limestone dusts, as far as their respective effectiveness is concerned in impeding coal dust explosions, was confirmed over and over again. The results obtained during investigations carried out in the American *EM Bruceton* are concordant with Polish results.

In the *EM Barbara* investigations were also carried out on the degree of the decomposition of limestone dust during coal dust explosions. On the basis of these investigations the quantities of the absorbed heat as well as the quantities of the educed carbon dioxide were estimated. The relevant computations indicated the absence of serious grounds for attributing more effectiveness to the limestone dust than to the clay-slate dust. In addition to this, comparative tests were made of the clay-slate and limestone dusts, respectively, when used on barriers [26]. These tests likewise did not disclose any differences in the effectiveness of the two dusts. Consequently, it can be considered to be a well established fact that the clay-slate, limestone and dolomite dusts are equally effective in suppressing the danger of the propagation of coal dust explosions.

The above statements does not change the fact that the use of clay-slate dust in mines is not to be recommended on account of the high content in it of free silica. Limestone dust exclusively is now used in Polish mines. It has an additional merit since, being white, it improves the visibility in the workings in which it is used.

According to American investigators [85] the following substances act obstructively upon the development of the flame in the coal dust cloud (in the order of the growing effectiveness): calcium carbonate, calcium carbonate made from pulverized oyster shells, Halon 1301 (trifluorobromomethane), Halon 1211 (difluorochlorobromomethane), sodium chloride, potassium chloride, sodium bicarbonate used in fire extinguishers, potassium bicarbonate, potassium bicarbonate with urea.

8.7.3. Waterproof dust

The limestone dust, similarly to the clay-slate dust, is much more hygroscopic than coal dust. In the humid mine air the relative humidity of which approaches 100 percent the surface layer of stone dust distinctly loses its dispersibility already after the lapse of a fortnight. The loss of the dispersibility of this dust becomes very rapid when it lies on a humid base — that is, on a humid rock or a humid coal dust. In such conditions stone dust absorbs the humidity from the base and also from the surface exposed to the action of the air. It ought to be understand that quite small quantities of the humidity absorbed by stone dust suffice to deprive it of its dispersibility. This phenomenon is explained by the influence of the humidity concentrated on the surface of the dust's layer. Even small quantities of humidity influence to a marked degree the cohesion of the dust particles. In consequence, a dust of a very low content of humidity, for example, 2 percent or even less, frequently creates the impression of being very humid because it shows no dispersibility; such a dust is called dead dust.

Coal dust is considerably more impervious to the influence of humidity. Fine coal dust spread in a thin layer over the surface of water does not sink but floats on it a long time. In the same conditions stone dust sinks quickly. The majority of our mines of bituminous coal are humid. This humidity, however, is insufficient in very many cases to prevent an explosion of coal dust as has been explained in Section 3.3. The problem of safeguarding such workings against explosions is quite difficult at times. The appropriate way of making the dust safe in such workings is the ample spraying of it with water as discussed in Section 8.5. When there is a water supply provided in the working by pipes under pressure the spraying does not present any difficulty. When there are no water pipes, however, other means of protection ought to be looked for because zones containing dangerous coal dust must not be left unprotected.

The use of stone dust in such humid zones is connected with practical difficulties since the dust spread in such workings loses its dispersibility very soon and becomes entirely ineffective making it necessary to repeat

the dusting. Likewise stone dust barriers, which will be discussed in Section 9.1, situated in humid places often require a change of the dust already after the passage of only a fortnight. Under such conditions the maintenance of a proper protection against explosions becomes both very expensive and rather dubious.

Keeping in view the above discussed difficulties a waterproof limestone dust was produced in the *EM Barbara* similarly to what was done in other countries. In order to make limestone dust, or any other stone dust, waterproof small quantities of fatty acids, for example, of stearin, have to be added during the process of grinding the lumps of limestone. Instead of the natural stearine other hydrophobic substances may be added such as the synthetic stearin, synthetic pitch, olein or tallow acids. To make the limestone dust sufficiently waterproof the addition of between 0.15 and 0.25 percent of the above mentioned substances is all that is necessary. The hydrophobic substance covers with a thin layer the particles of the dust and prevents for a long time their humidification [25]. The waterproof dust remains dispersible during a long time in humid and even in wet conditions, for example, on barriers it shows a high dispersibility after a longer period of being kept in humid conditions (100 percent of the relative humidity). When fresh the waterproof limestone dust is more dispersible than the ordinary limestone dust. In bulk it is more loose than the ordinary dust because its cohesion is distinctly weaker. The high dispersibility of the waterproof dust is obviously its very positive property as far as the prevention of the coal dust explosibility is concerned. Unfortunately this dispersibility causes the dust to be carried by the flow of air much further than the ordinary dust, which is particularly annoying to persons working in the places through which the dusty air flows. Taking these considerations into account the dusting with either the waterproof or the ordinary stone dust should not be done during the coal winning shifts; the best time for doing it is when the getting of coal is not in progress — that is, on holidays.

Though limestone dust does not contain much free silica, usually about 1 percent or only slightly more, yet the inhaling of it is irritating and cannot be regarded as entirely harmless for that matter, much the same as the inhaling of any mine dust. The requirements with regard to the limestone dust used in mines are listed in the BN-65/6791-08.

8.7.4. The way of measuring the dispersibility of stone dust

Among the basic requirements with regard to stone dust is listed, naturally, its ability to retain the dispersibility. The examination of the

dispersibility of the dust in mines is made in a very primitive way by blowing on a sample of the dust placed on the person's palm. Actually many experiments were carried out in various countries in order to work out methods of a precise ascertainment of the degree of the dispersibility of dusts. These attempts produced no serviceable practical solutions. In the *EM Barbara* an apparatus was designed — the *Barbara-LPW1* — which is used for the above purpose [160].

As the measure of the dispersibility of stone (limestone) dust is usually regarded its ability to be raised to the air and become dispersed in it in the form of a cloud under the influence of the air blast.

The principle of the *Barbara LPW1* apparatus consists in a short duration impact of an air blast on stone dust, and a photometric measurement of the density of the produced dust cloud. The blast of the air of a short duration is produced by a sudden release of compressed air from a container through a nozzle directed to the sample of the dust. The permanent value of the energy of the air blast is obtained by the invariability of the container capacity, the initial pressure of the air, the nozzle diameter and the geometric arrangement of the entire system. The examined sample of stone dust is standardized.

The cloud of the dust is formed in a closed chamber and, therefore, the variable external factors have no influence on its formation.

The density of the cloud is measured at a specified height in relation to the position of the sample by an aggregate consisting of the source of the light, a collimator and a photoelectric sensor, the last named element being composed of a set of photoemissive cell diodes.

This apparatus assigns the density of the cloud to one of the following three specified categories representing the conventional classification of the dispersibility of the dust by degrees, namely: the inadequate, sufficient and good.

The impulse of the photoelectric sensor is analyzed by two amplitude discriminators in which the thresholds of the relay system signals are being adjusted during the calibration of the apparatus with model dust samples.

The impulse relayed to the discriminators is the stronger the greater is the density of the cloud — that is, the higher is the dispersibility of the dust. Depending on the voltage of the impulse two indicator incandescent lamps are lighted when the dispersibility is good, one when it is sufficient. The lamps are not lighted when the dispersibility is inadequate. In this way the evaluation of the dispersibility of the dust is exceptionally simple.

In Fig. 8.21 the construction of the apparatus is shown in a schematic outline. The described apparatus can be used in factories as well as in

mines for testing the delivered dust and also for the periodical examination of the dispersibility of the dust on the barriers.

It would be more satisfactory to use the apparatus under the ground in order to avoid any changes in the humidity of the limestone dust during the transportation of the sample to the laboratory; the results of the examination would show the actual dispersibility more accurately.

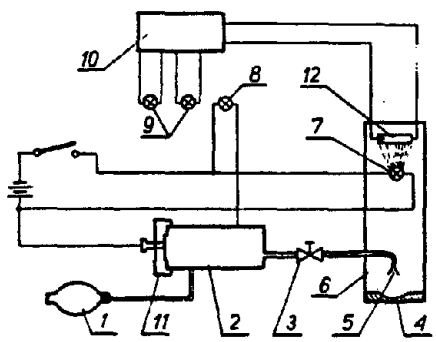


Fig. 8.21. The *Barbara-LPW1* apparatus for the ascertainment of the dispersibility of limestone dust used in mines: *1* — rubber bulb; *2* — compressed air container; *3* — full-bore type valve; *4* — dust sample; *5* — nozzle; *6* — closed dispersion chamber; *7* — source of light; *8* — lamps of pressure indicator; *9* — indicator incandescent lamps for determining the degree of dispersibility; *10* — the electronic system; *11* — container pressure sensor; *12* — photoelectric sensor.

8.7.5. The effect of the content of incombustible solid matter on the velocity of the coal dust explosion flame

To this question many experiments were devoted in the *EM Barbara* on account of both the theoretical and the practical importance of it. Unfortunately it was not possible to investigate the influence of the entire relevant scale of the contents of incombustible solid matter upon the velocity of the coal dust explosion flame. The coal dust which is called pure — that is, containing only the natural content of incombustible solid matter characteristic of the given seam produces high flame velocities during explosions. According to experiments carried out in the *EM Barbara* the velocity of about 1000 m/sec is attained easily even in the case of the relatively low degree of the fineness represented by the d25 coal dust.

Explosions of the pure coal dust containing more than 20 percent of volatile matter are exceedingly violent and cause far-going destructions in the experimental galleries as well as on the surface. Therefore, explosions of this kind were as a rule avoided in the *EM Barbara*, and the protection against the consequences of such explosions was sought by turning the end sections of experimental galleries into a zone of pure stone dust, or by placing there stone dust barriers.

For reasons explained above systematic investigations on the influence of the contents of incombustible solid matter on the velocity of the explosion flame were not made at all with regard to the range of violent

explosions the flame velocities of which exceed the mark of 500 m/sec. Nevertheless in the course of very numerous experiments the velocities of the flame about 1000 m/sec were attained in certain sections of experimental galleries. But such results were rather unforeseen in the experiments in question.

Finally the investigations were carried out, with an adequate accuracy, on the dependence of the flame velocity upon the content of incombustible solid matter only in the range of this content approaching the fading point of the ability of propagating explosions. The investigations in question were carried out in the 400 m experimental gallery with the 30mPII initiator and in the easiest dispersion conditions. The *d*85 and *d*25 coal dusts were used.

Thirty-eight tests were made of the dependence of the flame velocity on the content of incombustible solid matter n for the *d*85 *Barbara* dust. The results of these tests are presented in the graphic form in Fig. 8.22*a*. In this figure a regression curve is plotted for the range of the incombustible solid matter contents between 62.5 and 80 percent. The equation of the regression curve was found

$$v = 35857\left(1 - \frac{7.8}{100}\right)^n \tag{8.10}$$

The correlation coefficient $r = -0.9530$.

The absolute value of this coefficient is higher than the critical value $r_{0.05} = 0.497$ for the confidence coefficient $\alpha = 0.05$ and for the degree of freedom number $k = 14$. This means that there is a dependence between the mean velocity of the flame and the content of incombustible solid matter n.

The regression equation shows that when n grows by 1 percent the flame velocity declines on the average by 7.8 percent in relation to its former value.

Likewise, on the basis of 31 tests, a straight regression line was traced representing the dependence of the flame velocity on the content of incombustible solid matter for the *d*25 *Barbara* dust in the 400 m experimental gallery (Fig. 8.22*b*).

The equation of the straight regression line is

$$v = 444 - 5.9n \tag{8.11}$$

The straight line shown in Fig. 8.22*b* is determined for the range of n between 55 and 65 percent. The correlation coefficient $r = -0.9324$. The absolute value of r is higher than the critical value $r_{0.05} = 0.632$ for $k = 8$. The average decline of the flame velocity per 1 percent increase in the value of n amounts to about 5.9 m/sec.

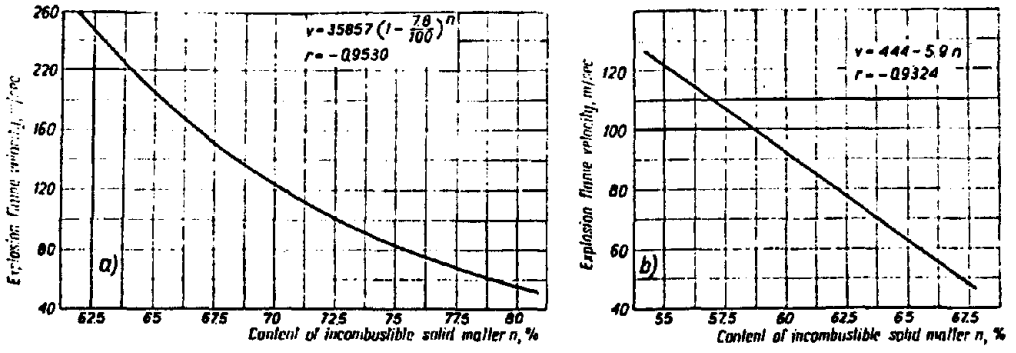


Fig. 8.22. Graphs of the interdependence between the mean velocity of the flame v and the content of incombustible solid matter n in the $d85$ and $d25$ coal dust (tests carried out in the blind 400 m gallery): a — the $d85$ coal dust, initiator 30mPII; b — the $d25$ coal dust, initiator 30mPII.

The described tests were carried out in the 400 m blind experimental gallery.

A series of tests were also made in the 400 m gallery, connected with the 200 m gallery, with the d85 coal dust, the initiator used being 30mPII.

For the above test conditions the following equations of the straight regression line were found

$$v = 333 - 3.7n \qquad (8.12)$$
$$r = -0.7255$$

The straight regression line represented by the equation (8.12) refers to the same range of the content of incombustible solid matter as that represented by the regression curve (8.10).

The critical value of the correlation coefficient $r_{0.05} = 0.576$ for $k = 10$ is lower than the above absolute value of r. This proves that the examined correlation is a real one.

The average decline of the flame velocity with the increase of n by 1 percent amounts to 3.7 m/sec and, consequently, is much lower than in the case of tests carried out in the blind 400 m gallery. This conforms to the results of investigations discussed in Section 6.4.3 on the influence of a connection between galleries upon the explosibility of coal dust.

Unfortunately, as has been pointed out already, the rather sufficiently precise results presented here of investigations on the interdependence between the flame velocity and the content of incombustible solid matter n in the *Barbara* coal dust containing volatile matter $V \approx 41$ percent refer only to a rather narrow range of the contents of incombustible solid matter n.

On the basis of very numerous results of investigations on the explosibility of coal dust obtained in the 200 and 400 m experimental galleries in the *EM Barbara* the interdependence mentioned above could be extended to include incombustible solid matter contents of about 50 percent. The results of investigations have been documented very carefully in the *EM Barbara* but the obtainment of data sufficiently precise to be analyzed statistically would have required a separate elaboration since the values of the flame velocities measured at particular sections of the gallery had fluctuated considerably.

8.7.6. American investigations on the effect of the content of incombustible solid matter on the velocity of the coal dust explosion flame in the light of the analysis made by British investigators

British investigators [77] studied the problem of the effect of incombustible solid matter contents on the velocity of the coal dust explosion flame, and have analyzed the results obtained by American [143] and Polish investigators.

On the basis of their analysis of American investigations, carried out in the *EM Bruceton*, the British investigators have worked out a schedule, presented in Table 8.4, illustrating the effect of the incombustible solid matter content on the flame velocity.

Table 8.4

Influence of the Content of Incombustible Solid Matter on the Flame's Velocity (Worked out by Eisner and Shaw on the Basis of the Results of Investigations Carried out at the *EM Bruceton* [77])

Total content of incombustible solid matter	Number of experiments	Number of experiments in which flame velocities had been established exceeding:			
		650 m/sec		980 m/sec	
		number	%	number	%
<12.5	18	10	55	6	33
>12.5	183	6	3.3	0	0

Though the Table 8.4 contains very general data, yet this data is interesting. The American investigators have only in six cases established flame velocities reaching to approximately 1000 m/sec. Unfortunately even this number of cases cannot be regarded as certain because, at the time

when the pertinent investigations have been carried out, the method of measuring flame velocities at *Bruceton* could produce very questionable results particularly at very high flame velocities found at *Bruceton* for pure coal dust.

It is interesting that, with contents of incombustible solid matter $>>$ $>$ 12.5 percent, only in 3.3 percent of tests velocities exceeding 600 m/sec were recorded. Unfortunately this data conveys very little since for each one of the six mentioned experiments the fineness of the coal dust and the content of incombustible solid matter ought to have been given.

The British investigators referred to have also analyzed the results obtained by the author of this book.

According to the opinions expressed by these British investigators on the basis of analyses made of their own, the American and the present author's investigation results, even a very inconsiderable addition of stone dust to coal dust causes a very marked decrease of the flame velocity. Already when 5 percent of stone dust is added an evident reduction of the explosion flame velocity is observed amounting to from 20 to 60 percent of the flame velocity recorded under conditions involving the presence of pure coal dust. The addition of about 40 percent of stone dust causes the reduction of the flame velocity by from 50 to 90 percent.

Though the results of investigations carried out in the *EM Barbara* confirm the influence of the addition of stone dust on the velocities of the explosion flame, yet the values given by the British investigators seem to be too high.

In any case there is no doubt that pure coal dust presents a particularly serious danger and that even a relatively inconsiderable addition of stone dust — that is, much smaller than that required by regulations, could seriously influence the course of a coal dust explosion, especially when explosion initiators are weak.

8.7.7. The disadvantages of dusting mine workings with stone dust

8.7.7.1. The toilsomeness of dusting mine workings with stone dust. The dusting of workings with stone dust is very toilsome considering that the content of incombustible solid matter in coal dust, required by regulations, is high. In order to make dangerous coal dust safe all workings in which such coal dust is present ought to be stone dusted so as to bring the content of incombustible solid matter to a level which makes the particular coal dust incapable of propagating an explosion. The dusting by hand is very expensive. The mechanical dusting, on the other hand, causes the stone dust to be carried over a long distance by the air flow making it impossible to use this method when men are present along the way of

the air flow. The compliance with the regulation requirements is particularly toilsome in ascending galleries.

The dusting of the entire cross section of a working with stone dust is difficult especially where workings are high. The above remarks are of a general nature only since locally special difficulties may appear.

8.7.7.2. Special difficulties connected with an effective dusting of workings with stone dust. During a coal winning shift coal dust steadily deposits itself beginning with the face of the working all the way to the winding shaft along the conveyor roads as well as ventilation roadways. The dusting with stone dust is performed periodically — that is, every now and again. In consequence there is always a chance for coal dust to be present on the surfaces of workings. During an explosion of coal dust it is exactly the surface layer of the dust that plays the most important part because, as was mentioned already in Section 6.1, this layer is the easiest to raise to the air.

The course of a coal dust explosion is determined by the cloud of the dust raised to the air. In its turn the composition of such a cloud is determined decisively exactly by the surface layer of the dust. In the outcome the dust present in a working can show a very high content of incombustible solid matter, and yet be not safe as regards its capability of propagating an explosion. Such cases are known in the mining practice. Such occurrences, indeed, have been established through investigations carried out after actual dust explosions. By way of an example the explosion can be referred to which took place at the *Łagiewniki* mine in 1956 and in which eight men lost their lives. The explosion of coal dust developed in workings and passed a route 440 m long in spite of the fact that the content of incombustible matter in the dust reached up to 80 percent. But the surface layer had been much richer in carbon. It should be mentioned that this explosion could have had much more disastrous effects, had it not been stopped by a stone dust barrier.

The difficulties of an effective dusting with stone dust are felt particularly strongly in such workings in which coal dust deposits itself in large quantities. These difficulties depend manifestly on the quantities of coal dust deposited in the working in a unit of time.

Belt-conveyor roads are especially difficult to be effectively protected by stone dust against the propagation of explosions. In such roads coal dust settles in large quantities. The entire structure of belt conveyors is normally dusty with very dangerous coal dust. Besides, large accumulations of coal dust are formed in the vicinity of the transfer and discharge points.

A correct dusting with stone dust of the belt-conveyor construction is practically impossible. In Section 6.2 the hazard of the propagation of

coal dust explosions was discussed with reference to workings in which there are longitudinal zones with dangerous coal dust.

The dusting with stone dust, the aim of which is to attain the regulation content of incombustible matter in the dust of the working, presents the greater difficulty the larger are the dust accumulations. In some workings the large accumulations of dust are due to the lapse of a long time during which coal dust deposits were allowed to accumulate without being removed from the workings.

8.7.7.3. Pollution of the won coal by stone dust. To avoid the pollution of coal the dusting with stone dust is not done in the actually exploited workings nor at the faces of galleries of a cross section area exceeding 10 sq m. The zones which have to be dusted begin, according to regulations actually binding in Poland, at the distance of 4 m from the face, or 4 m from the longwall outlet or the shortwall opening. As a result the dusting with stone dust of conveyor roads and narrow-gallery faces causes a considerable pollution of the output. This is particularly disadvantageous where coking coals are concerned which, regardless of the degree of their fineness, are very valuable. The pollution of the coal winnings with stone dust is a great disadvantage of the method discussed here.

8.7.7.4. The mass density of stone dust and of coal dust. The mass density of "pure" coal dust oscillates within rather wide limits depending on the seam; in the case of coals exploited in Poland these limits are from 1.257 to 1.922 g/cu cm the mean value of the mass density in question amounting to about 1.38 g/cu cm. On the other hand, the mass density of the limestone dust used for dusting mine workings amounts to 2.64 g/cu cm. Thus, coal dust is of a much lower mass density. This fact exerts a serious influence on the distribution of these two dusts in the dust layers in mine workings. Generally whenever a mixture of coal and stone dusts is raised to the air, and this, for example, always takes place during shotfiring operations, the limestone dust, being the heavier of the two, settles first and the coal dust, as the lighter one, settles afterward. In this way coal dust tends to form the surface layer in a mine working. As was mentioned already this phenomenon occurs in particular and, clearly, during shotfiring operations. In what measure this affects the danger of a coal dust explosion is illustrated by the very unusual explosion accident in the *Nowy Wirek* mine in the year 1959.

In this mine a crosscut was driven in sandstone. At the time of the disaster 10 percent of the face surface showed the coal of the seam which was being uncovered. The field in which the works were conducted contained no methane and the driving of the crosscut was done with rock dynamite in sandstone and with permitted nitroglycerine explosive B in coal. Shotfirings in coal were done separately as in this way a better cut

was attained. Humid conditions prevailed in the crosscut. During the firing in sandstone of rock dynamite charges, with electric one-second delay detonators, a local explosion of coal dust occurred. The range of the explosion flame was about 40 m. In consequence of this explosion one miner was killed — the cutter-shotfirer who executed the shotfiring.

After the accident it was found that the total content of incombustible solid matter in the dust present in the working had been quite sufficient as a protection against the propagation of an explosion. However, the surface layer of the dust in the vicinity of the face contained only about 20 percent of incombustible solid matter. This dust was capable of propagating an explosion a fact fully corroborated by the course of the explosion in question.

The dangerous thin surface layer of pure coal dust had been formed during shotfiring operations both in coal and in sandstone. Shotfiring in sandstone produced a blast which raised the dust in the vicinity of the face with the effect that stone dust settled first and that coal dust, being lighter of the two, deposited itself on the surface of the former. In this way a dangerous surface layer of coal dust had been formed which was raised to the air by the firing of dynamite charges in six shotholes. One of the shots caused the ignition of the coal dust cloud an accident obviously easy to have happened considering that the rock dynamite and electric one-second delay detonators were used. The accident described above illustrates the danger of the coal dust depositing itself on the surface of rock-and-coal workings and demonstrates the possibility of a dust explosion even in the presence of a small surface of coal at the face of the working.

The above description ought to be supplemented by the information that the sandstone dust was more humid and the coal dust considerably drier.

8.7.7.5. Difficulties connected with controlling the effective dusting of workings with stone dust and the methods of taking samples of the dust. As the first among the difficulties to be considered one ought to mention the impossibility of establishing on the spot whether the dusting with stone dust had been performed according to regulations. Only in cases of a sheer neglect of the dusting it can be seen that no dusting was performed.

The only method of control employed so far is the collecting of dust samples and analyzing them in order to determine the content of incombustible solid matter in the dust. But there are many difficulties connected with this method.

The dust conditions in the zone which is to be controlled are not uniform in respect of the presence of coal dust deposits and in respect

of the dusting with stone dust. The dusting is the most uniform when it is performed mechanicaly. Naturally when the dusting is done by hand considerable differences are likely to occur along the examined zone.

As was explained in Chapter 6 the course of a coal dust explosion is affected decisively by the composition of the cloud of coal dust raised from the surface of the dust deposits. Therefore, in order to evaluate the extent to which the dust is made incapable of propagating an explosion it would have been necessary to collect a sample of only that surface layer of the dust which can be raised to the air. Taking into consideration the great diversity of surfaces in mine workings it is easy to realize how difficult it is to collect correctly a really representative sample of the dust.

Considerable differences are to be found between the chemical composition of the dust deposited on the floor, on the sidewalls, on roof bars, pipings and, in general, in the upper parts of a working. As has been demonstrated by large scale investigations on the influence of the distribution of the dust upon its explosibility, it is exactly the dust deposited in the upper parts of a working that plays the most serious role. Moreover, systematic analyses of the samples of mine dust collected in mine workings proved that the dust deposited on roof bars and, generally, in the roof parts of a working is much more dangerous than the dust deposited on the floor (see Section 8.7.8). Consequently, in order to determine whether the regulation requirements had been complied with it is necessary to collect dust samples separately from the upper parts of a working and separately from the floor. Of course it is practically impossible to collect dust samples from the entire surface of the examined zone. It is, therefore, necessary to collect the samples from points in the zone placed at some distance from each other, so as to make certain that the samples should be representative for the determination of the content of incombustible solid matter in the dust present in the examined zone.

In the *EM Barbara* many investigations were carried out on the methods of collecting dust samples for the purpose of determining the contents of incombustible matter.

The most commonly used method is the so-called strip method consisting in the collection of 5 mm layers of comminuted coal from strips 20 cm wide encircling the circumference of the working. The distance of the first strip from the face of the working should be 10 m.

If the dustiness within the cross section area of the working is diversified the samples ought to be collected separately from the floor, the sidewalls and the roof parts. The contents of incombustible matter in each of the above samples should conform to regulation requirements.

The number of strip samples collected in a 200 m zone should not be less than five.

The samples collected in the examined zone have to be carefully mixed together before being sieved and a mean sample is then collected from the mixture.

In the case of a dry dust it is sifted with a sieve of a 1 mm mesh. A humid dust is first sifted with a sieve of a 3 mm mesh and, then, after it is dried, a sieve of a 1 mm mesh is used. Of the fractions < 1 mm again a representative sample is collected and this sample is analyzed for the purpose of determining its physicochemical characteristics.

In the *EM Barbara* extensive investigations were also carried out on the so-called "points" method of collecting dust samples [165]. This method consists in collecting dust samples from circular surface areas of a diameter of 20 cm. As in the case of the strip method the samples in the "points" method ought to be collected beginning from a distance of 10 m from the faces of gallery, longwall or shortwall workings. The distances between the particular series of "points" sample collection should not be longer than 20 m. It is clear that the "points" method is more convenient and makes possible a quicker collection of dust samples in a given working.

The ways of sample collections by the "strip" and the "points" methods are schematically shown in Fig. 8.23.

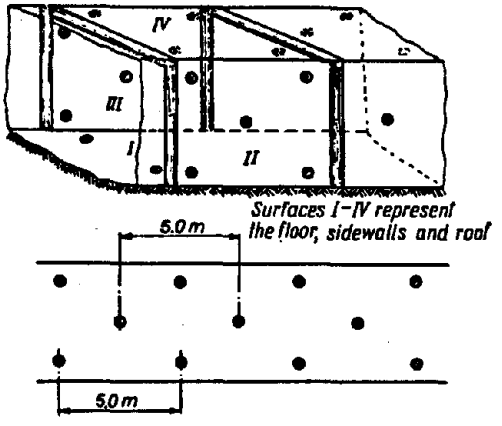


Fig. 8.23. A schematic presentation of the way of collecting dust samples in a roadway employing the strip and the points methods.

Naturally it is impossible to observe strictly the rule that the samples of the dust should be 5 mm thick. This thickness should be regarded as being given for a general orientation.

A comparison of the results obtained by the "strip" and the "points" methods was made [165]. Experiments were carried out in 13 workings in seven mines.

Denoting the contents of incombustible matter determined by the "strip" method by the symbol n_a and the same contents determined by the "points" method by the symbol n_b it was found that the comparative value $\frac{n_b}{n_a} \cdot 100\%$ oscillated between 98.9 and 103.9 percent.

Thus it was established that the differences between the results of determining the contents of incombustible matter by either of the two methods are insignificant.

In the course of the same work [165] the interdependence had been examined between the thickness of the collected layer of the dust and the determined content of incombustible solid matter. The comparisons were made for the thickness from 0 to 5 mm and for the thickness >5 mm. Altogether 27 tests were made. It was found that the differences between the contents of incombustible solid matter in the layers of dust of either of the above ranges of thicknesses were insignificant and that this conclusion is valid for the dust fraction <1 mm as well as for the dust fraction <75 μm.

The above comparison results may be considered as rather unexpected.

Thus a necessity arises of carrying out very careful investigations, planned on a large scale, on the contents of incombustible solid matter as depending upon the thickness of the dust layer. The thinnes possible surface layers of dust, not exceeding 1 mm, should be considered in such investigations. Naturally, the results obtained should be compared with the contents of incombustible solid matter in specified thicker layers. The investigations in question ought to be carried out in various typical workings with particular attention paid to dust deposits in the upper parts of the workings.

In view of the decisive role of the surface layers of dust the investigation work along the lines discussed above has already been undertaken in the *EM Barbara*.

8.7.8. The advantages of dusting with stone dust

The above described disadvantages of dusting mine workings with stone dust could hardly justify the widespread use of this method were it not for the essential advantage it offers consisting in the fact that a reasonable use of dusting with stone dust, according to regulations based on the results of basic investigations, makes it possible to render coal dust incapable of propagating explosions. In spite of having many disadvantages and in spite of the toilsomeness of the operation, the dusting with

stone dust gives, on the scale of the world mining industry, unquestionably favorable results. This is confirmed by the world statistics. Since the time of the general introduction of this method the number of disasters caused by explosions diminished and, consequently, the number of fatalities likewise has fallen off considerably.

At first, over a period of years, the regulation requirements in this field were quite inadequate as they were not based on the results of investigations. During the period between the wars, according to the majority of binding regulations, it was necessary to maintain 50 percent of incombustible solid mater content in the mine dust. Only in some, not very numerous cases, such a content of incombustible matter could protect against the propagation of explosions provided that the distribution of coal dust, its fineness, its humidity and the explosion initiator were not favorable to the development of an explosion.

In many cases of explosions it was found that even these modest requirements were not complied with.

Though the regulation requirements were quite inadequate their fulfilment did in many cases restrain the violence of explosions in comparison with situations in which pure coal dust had been present.

The results of investigations, discussed in preceding chapters, supplied evidence of the necessity of higher contents of incombustible solid matter in the dust in order to provide a protection against the propagation of explosions. One must admit that scientific research institutes, in demonstrating this fact, acted with a certain rather obvious timidity. As is already known from the preceding chapter the explosibility of coal dust, measured by the contents of incombustible solid matter which make the dust incapable of propagating explosions, depends upon many factors. These factors can be arranged for particular experiments in a manner leading to the finding of lower contents of incombustible solid matter, necessary to give protection against the propagation of explosions, than those that are determined by experiments for which conditions are created corresponding to the most unfavorable conditions encountered in practice. Under such conditions investigations were carried out in the *EM Barbara* (as, e.g., those described in Section 6.5) and also in some foreign scientific research institutions.

One of the advantages of the dusting with limestone dust is the improved visibility in mine workings resulting from their white surfaces.

8.7.9. Regulation requirements for making coal dust incapable of propagating explosions through dusting of workings with stone dust

Regulation requirements, pertaining to the dusting of mine workings

with stone dust, in force in different countries represent in principle a certain compromise in relation to the contents of incombustible solid matter determined by scientific research institutions. The contents of incombustible solid matter, required by binding regulations in different countries, are listed in Table 8.5; there are considerable differences between them.

As can be seen in Table 8.5, in general, the regulation requirements in many cases are undoubtedly inadequate to make coal dust incapable of propagating explosions in very dangerous circumstances which, after all, do occur in practice.

Here we should remind ourselves of the results of investigations carried out in the *EM Barbara*, scheduled in Table 6.10, in which very extensive investigations are summed up executed along the 200 and 400 m zones. They refer, in a general way, to bituminous coals containing more than 25 percent of volatile matter; for example, in order to ensure that the *d*85 coal dust should not be capable of propagating an explosion up to 200 m the value of n must amount to 88.7 percent, the probability P being equal to 10^{-2}; the same dust, if it contains $n = 80.5$ percent, makes the probability of propagating an explosion over a 200 m zone $P = 5 \cdot 10^{-1}$.

Similarly to make the *d*25 coal dust safe in the same conditions the value of n must be 77.5 percent with the probability $P = 10^{-2}$; the same dust with $n = 67.9$ percent, makes the probability of propagating an explosion over a 200 m zone $P = 5 \cdot 10^{-1}$.

In order to be safe as regards the propagation of an explosion over a distance up to 400 m the relevant values of n are lower as indicated in Table 6.10; yet, if an explosion is allowed to develop over such a distance the usual consequences are disastrous and cause a great number of fatalities.

When the values of n referred to above are compared with regulation requirements listed in Table 8.5 the clear conclusion is that regulations binding in different countries are inadequate. This accounts, among other things, for the repeated occurrence of explosion disasters. It is necessary to underline again the fact — as was explained when the disadvantages were discussed of the dusting with stone dust — that the most important role is played by the surface layers of the dust which usually contain much more carbon substance than the deeper layers of dust deposits. As a result, the regulation requirements listed in Table 8.5 are either inadequate or provide only a very narrow margin of safety. Apart from the obligatory values of n a great role is played by the required range of the dusting with stone dust, or — to put it in a more general way — by the range along which coal dust ought to be made incapable of propagating an explosion. When the required values of n are to be maintained only along the 200 m zones, counting from the points at which explosions are initi-

Table 8.5

A Schedule of the Contents of Incombustible Solid Matter Required by Regulations in Force in Various Countries in the Year 1970

Country	Date of the enactment of regulations	Incombustible matter content corresponding to the volatile matter content		The scope of the dusting or spraying of workings:	Distance of zone to be dusted from the gallery's face	Remarks
		incombustibles %	volatiles %		m	
1	2	3	4	5	6	7
Austria		—	—	all workings are sprayed with water	—	
England	1963	50	20	all workings are stone dusted, except the coal getting workings	10	
		55	22			
		60	25			
		65	27			
		68	30			
		70	32			
		72	35			
		75	> 35			
Belgium	1965	60	14	as above	—	
		78	> 26			
Czechoslovakia	1961	80		all workings are stone dusted except small shafts, transfer points and coal getting workings	4	
France	1963	50	< 22	all workings are stone dusted except coal getting workings and workings protected with pastes	as close as possible to the face	
		55	22–24			
		60	24–26			
		65	26–29			
		70	> 29			

Table 8.5 (continued)

1	2	3	4	5	6	7
Holland	1965	65 80	22 > 29	as above	—	with CH_4 contents up to 1.5%
Canada	1959	65	> 14	as above	10	to every 0.1% of CH_4 1% of incombustible solid matter ought to be added
GDR	1963	70	—	as above	no information available	
FRG	1964	80	—	hygroscopic pastes are used in all workings	no information available	
Poland	1953	nonmethane seams 70 methane seams 80	 > 12 > 12	up to a distance of 200 m workings are stone dusted except coal getting workings	4	recently amended
Rumania	1969	as determined by the Institute	> 10	up to a distance of 200 m workings are stone dusted except coal getting workings	no information available	
USA	1960	65	> 20	workings are stone dusted	—	to every 0.1% of CH_4 1% of incombustible solid matter ought to be added
USSR	1964	as determined by the Institute with requirements: > 60% control every 3 years; < 60% control every year	> 10	zones 300 m long are stone dusted except coal getting workings	as close as possible to the face, the immediate vicinity of the face is subject to daily spraying or dusting	

ated, then there is a danger of a great disaster if an explosion should become propagated beyond the mentioned zones and were to enter the workings in which coal dust is not made safe from participating in the propagation of explosions.

The number of zones which must be protected against the propagation of explosions (which must be dusted with stone dust) is quite considerable. It is difficult to feel certain that in all of these zones regulation requirements will be irreproachably complied with. The world practice shows that there can be no certitude in this matter.

The matter in question is bound up with the erroneous assumption that a coal dust explosion can be initiated only by a local explosion of firedamp or by shotfiring operations. In Chapter 5 other really existing possibilities of the initiation of coal dust explosions in mines were discussed.

Where only 200 m zones in mine workings are protected against the propagation of explosions, very strict requirements insist on the use of stone dust or water barriers. Such barriers are known to have prevented many a serious disaster in the past.

Summing up the above remarks it should be stated that in some countries the danger of coal dust explosion disasters is sanctioned by the binding regulations which do not correspond to the results of scientific investigations. But it must be said also that the relevant regulations are being gradually amended or, in particularly dangerous conditions, the mining authorities issue orders introducing stricter requirements.

The progress of science and technology develops so naturally that unquestionably the regulations pertaining to the prevention of danger of coal dust explosions will, eventually as the consequence of new research works, correspond to scientific conclusions. The fully understood necessity of utilizing science for industrial progress is a guarantee that things will progress in the above indicated direction.

The problem of making coal dust incapable of propagating explosions, by means which are well adapted to conditions existing in mines, is solved in the main. The means in question are discussed in Sections 8.10, 8.11 and 8.12.

8.8. PREVENTING THE DANGER OF THE PROPAGATION OF A COAL DUST EXPLOSION BY MEANS OF BINDING THE DEPOSITS OF THE DUST

8.8.1. General information on the methods of binding coal dust deposits

In matters concerning the propagation of explosions the decisive role is played by the surface layers of the mine dust because the explosive

properties of the system which is being formed before the front of the flame (Section 6.1) depend upon the composition and the density of the dust cloud in the cross section of the mine working. Clouds of dangerous coal dust, formed even in a relatively small part of the cross section of the working, are capable of propagating an explosion (Section 6.2).

A layer of pure dispersible coal dust on the surface of a working, 0.1 mm in thickness, is sufficient to create an explosion. To counteract a steady deposition of coal dust it would have been necessary to apply a simultaneous dusting with stone dust. As this cannot be realized in practice a frequent dusting with small quantities of stone dust is recommended in such workings. The procedure of this kind, however, obstructs mining operations and, when the settling of coal dust is steadily intensive, gives no certitude of an adequate protection. In the circumstances a different way of fighting the hazard of coal dust was sought since long ago. Namely, the possibility was considered of depriving coal dust of its dispersibility while the grains of the dust float in the air, or as soon as possible after the dust settles on the surface of workings.

In Great Britain [75] very penetrating investigations were carried out on the possibility of binding coal dust along the entire distance over which it was carried by the air flow and where it deposits itself. It was found that the best means to this end are water droplets of a mean diameter approximately 12 μm. Such droplets evaporate in a couple of seconds. In order to retard this process they are covered with a unimolecular layer of the cetyl and stearyl alcohols with an addition of a nonionic wetting agent. The water is sprayed by a special nozzle. The above very interesting method failed in practice to produce the expected results.

When the surface of a working is very humid or wet the coal dust depositing itself on it loses its dispersibility under the influence of water only after a certain time which can be reduced considerably by adding a wetting agent to the water used for spraying.

8.8.2. The saltcrust method

Chronologically the first method actually used in practice for binding the coal dust depositing itself in mine workings was the method of the salt (NaCl) crusts introduced in the *Beeckerwerth* mine by Schlochow and Rohe in 1945. In the German and English literature this method is known as the *Salzkrusten Verfahren* — the saltcrust process [12], [83], [122], [163]. This method consists in covering the surface of mine workings by common salt with water, the consistency of the mixture being that of a paste thus making it adhesible to the surface. Coal dust depositing on this saturated solution is caught. When the conditions are sufficiently dry the salt crys-

tallizes out of the saturated solution and the crystals which are formed come to the surface, while coal dust remains beneath them. In this way the coal dust becomes permanently bound. In order to repeat the process of the crystallization the surface layer of salt crystals has to be dissolved by spraying it with water. Thus the process runs in cycles.

The salt paste is sprayed with a cement gun. The periodical wetting of the salf surface must be made very carefully so as not to let water consume the salt layer.

When coal dust deposits itself intensively the spraying with water should be done several times a day which would naturally be very toilsome. Consequently, the employment of this method is justified in mine workings in which coal dust does not deposit itself very intensively and the spraying with water can be done not so frequently, for example, once a week.

The use of the saltcrust process is limited. The recrystallization process is possible when the relative humidity of the air does not exceed 70 to 75 percent. Actually this humidity limit depends upon the velocity of the air flow. When the velocity in question is 4 m/sec the humidity limit is approximately 90 percent and it is about 64 percent when the velocity equals 1 m/sec.

In Polish mines a low relative humidity is very rare so that the saltcrust process cannot be employed.

It can be easily conceived that the use of common salt on such a large scale must cause a serious corrosion of steel. Therefore the covering of the surfaces in mine workings with salt paste must be done with great care, all steel objects have to be scrupulously protected against coming into contact with salt. Very special care must be exercised to protect all electric appliances. But the result of this protection is that coal dust, depositing on objects protected against any contact with salt, does not become bound.

The author of the present book has had the opportunity to get acquainted with the described method at the *Beeckerwerth* mine mentioned already. Making a tour of the workings the author formed an opinion — based on what he had seen — that the method seemed to be effective.

British investigators [12] carried out very painstaking investigations on the employment of the saltcrust method in a mine gallery 300 yards long, over a period of 15 months. In the gallery in question the deposition of coal dust proceeded so intensively that, in order to provide an adequate protection, the dusting with stone dust would have to be done three times a week. By employing the saltcrust process coal dust remained bound during the two-day cycle.

The salt surface with coal dust embedded in it is very dark so that

the lighting in the working is worse than it is where limestone dust is used.

The British investigators have roughly estimated that the employment of the saltcrust process ought to be somewhat less expensive than the dusting with stone dust.

However, no investigations were made on the effectiveness of this method in making coal dust incapable of propagating explosions. When coal dust is bound permanently (as described above), it is safe. But the essential question concerns the speed with which coal dust becomes bound when it deposits itself intensively in a given mine working. One should judge that at least during a period of several hours, when the day's process of the deposition of coal dust is the most intensive, a sufficiently large deposit of free dust can accumulate to be capable to propagate an explosion. At any rate for pronouncing the saltcrust process to be effective it would be necessary to carry out experiments which will demonstrate that exactly during the time of the most intensive deposition of coal dust an explosion of coal dust will not develop over a zone protected by the saltcrust process. Such experiments, though very difficult, could be carried out but the necessity of undertaking them does not appear to be actually well founded.

In spite of being difficult to use, and in spite of the drawbacks mentioned above, the saltcrust process has certain advantages over the method of pastes, described in the next sections.

8.8.3. The method of hygroscopic pastes [91], [123]

Since long ago the advisability was considered of utilizing the properties of hygroscopic salts for binding depositions of coal dust. The $MgCl_2$ lye was first tried in 1910 as a means to this end. At that time, however, the results obtained have not been sufficiently good. As the turning point in the elaboration of the method of hygroscopic solutions is regarded the introduction of nonionic wetting agents. The introduction of these agents made it possible to work out effective methods of binding the coal dust deposits.

The introduction on a large scale of the method of hygroscopic pastes in the Federal Republic of Germany has followed the *Luisenthal* mine disaster of 1964.

According to regulations then binding in the Federal Republic of Germany the mine workings were dusted with stone dust but this did not prevent the disaster. Undoubtedly in the mine workings directly affected by this disaster the regulation requirements were not complied with but the occurrence of so great a disaster had definitely shaken the confidence

in the possibility of an effective dusting with stone dust under conditions existing in German mines. All the drawbacks of this method, discussed in Section 8.7.7, have been taken into consideration on this occasion.

As the result of many experiments, hygroscopic mixtures in the form of pastes were worked out in the Federal Republic of Germany. These pastes, spread over the surfaces of mine workings, deprive coal dust, which deposits itself there, of its dispersibility.

Actually two kinds of such pastes are in use, the basic components of which are either magnesium chloride or calcium chloride.

The paste in which magnesium chloride is the fundamental component is of the following composition (given in weight percentages): $MgCl_2$ — 6.42% (in approximately a 34% solution); H_2O — 31.3%; $Ca(OH)_2$ — 3.5%; nonionic wetting agent — 1%.

The paste based on calcium chloride is of the following composition (given in weight percentages): $CaCl_2$ — 90.4% (in approximately a 26% solution); $MgCl_2$ — 7.9% (in approximately a 34% solution); $Ca(OH)_2$ — 1.7%; nonionic wetting agent — 1.0%. The $Ca(OH)_2$ added to these pastes plays the role of the condensing ingredient.

The properties of the above pastes can be improved by the addition of special ingredients such as, for instance, the quar gum, commonly used for the gelatinization of waterproof explosives.

In appearance these pastes resemble a very humid sludge and they must be of an appropriate consistence. At first they were produced on the spot, in the mines, but now they are delivered ready for use by chemical factories.

The pastes are distributed below the ground in tank cars and this is a source of certain operational difficulties. Naturally this transportation ends where the rails end. Further distribution is done through a system of pipes with the aid of pumps. The pipes are sometimes as long as 1 km. The surfaces of workings are sprayed with the paste through specially manufactured nozzles. When the paste hardens either in the pipes or in the nozzles its removal presents difficulties. The coal dust depositing itself becomes bound through the hygroscopic properties of the pastes and through the action of the wetting agent and thus loses its dispersibility.

In the normal mine air the pastes do not dry up. Only when calcium carbonate is produced through the chemical reaction between CO_2 and $Ca(OH)_2$ the surface becomes tarnished here and there by the formation of crusts.

The dust-absorbing capacity of the pastes depends upon the properties of the coal dust. The finer is the dust the less of it can be absorbed by the paste. A well-marked influence upon the dust-absorbing capacity of the pastes is exerted by the degree of the carbonification of the dust. The

maximum dust-absorbing capacity of the pastes was established in the case of coal dust containing about 20 percent of volatile matter.

8.8.4. The method of hygroscopic powders [91], [123]

As mentioned above the transportation of the pastes and the covering with them of the surfaces of mine workings presents certain difficulties. In order to facilitate the use of hygroscopic salts they are supplied in the form of dry powders. The powder consists of $CaCl_2 \cdot H_2O$ with the addition of about 3 percent of a nonionic wetting agent and the same hygroscopic salt in the form of flakes.

In its essence the powder is also a paste from which it differs in this that the paste is formed on the surfaces of mine workings through the adsorption of water from the air. The powder does not contain any condensing ingredients. The role of these is taken over by the dust underlayer of the workings. The powder is being applied in the same way as stone dust. Pneumatic apparatus is used for this purpose and a good care must be taken that the compressed air should be sufficiently dry as otherwise the ejector becomes easily choked.

The transport of powder is much easier than the transport of pastes. But the sacks used for the purpose must be watertight and able to withstand difficult conditions existing in mines.

Since the method of powders in its ultimate effect is analogous to the method of pastes the discussion of their effectiveness and their drawbacks is applicable equally to either of them. Both methods can be referred to by the single name of the method of hygroscopic pastes.

8.8.5. The effectiveness of pastes in stopping coal dust explosions

In the experimental mine *Tremonia* (The Federal Republic of Germany) many investigations were carried out the aim of which has been to establish the effectiveness of the method of pastes in stopping developed coal dust explosions. It had been rightly assumed that an explosion of coal dust can have a certain running start along the zone not protected by paste directly adjacent to the face of a working. In these experiments the powder method was employed.

The first series of experiments were carried out in an experimental gallery 265 m long of the cross section area measuring 8 sq m. The running start zones of coal dust explosion were 50 and 80 m long.

With the running start zone 80 m long the next 150 m zone protected with paste proved to be sufficient to make the propagation of an

explosion impossible. An analogous result was obtained when the zone, adjacent to the running start zone, contained no mine dust (no information is available on the number of experiments carried out).

Further investigations were made in a gallery 740 m long the cross section area of which measured 8 sq m. The protection zone was arranged in the section of the gallery beginning at the distance of 150 m and extending to the distance of 350 m from the face of the gallery. The coal dust explosion flame reached the protection zone with a velocity of 90 m/sec and then, achieving the velocity of 200 m/sec during its passage through the protection zone, it carried the explosion to the zone in which coal dust was not protected.

On the whole these investigations did not produce unequivocal results. Explosions were sometimes stopped in, and sometimes propagated over, the protection zone 250 m long. In any case it was found that a protection zone of this length cannot be relied upon. After the passing through this zone the flame velocity amounted, for example, to 400 m/sec. Analogous results were obtained with a zone free of mine dust. Results obtained at experimental mine *Tremonia* are given here by way of an example.

With weaker explosions developing in two directions better results were obtained.

Though very scrupulously prepared, the experiments carried out at the experimental mine *Tremonia* produced no convincing evidence as to the effectiveness of pastes. It ought to be stated that the quantities of $CaCl_2$ used for covering the surfaces of the gallery were as large as 5 kg/sq m. There remains an open question (of which a mention has been made when the saltcrust process was discussed), quite apart from the described investigations, namely, the question of the time which it takes to bind coal dust when it deposits itself intensively. There is no evidence to support the view that the method of pastes acts quickly enough in making coal dust safe in respect of its capacity of propagating explosions.

The German investigators are quite correct when they say that the only reliable answer to the above question could be obtained by arranging explosions in each of the possible sets of concrete conditions and this is, obviously, an impossibility. The above statement is the best way of saying that the method is not quite dependable.

In describing their investigations the German investigators declare that the method of pastes ought to be employed together with water or stone dust barriers.

The method of hygroscopic salts in the form of pastes or powders is recognized by regulations binding in the Federal Republic of Germany as the basic method of preventing the danger of coal dust explosions. If

the management of a mine wished to dust the workings with stone dust a special permission of the mining authorities would have to be obtained.

We are entitled to think that the decisive role in the compulsory introduction of the method of pastes was played by the great potassium salts industry of the Federal Republic of Germany. It disposes of a tremendous base of waste products which can be successfully utilized in the manufacture of pastes. Getting rid of these products is connected with great difficulties on account of the prohibition of polluting rivers.

It ought to be stressed in particular that, apart from the question of the practical effectiveness of pastes which it is hard to place beyond dispute, the pastes are not at all entirely unharmful to the health of workers and their effects on the environmental conditions in mines are very negative in many respects.

8.8.6. Negative results of employing the method of pastes

The use of pastes is not at all entirely unharmful to the health of the miners. The pastes, as well as powders, could cause serious diseases of men by affecting their skin. People who are rather allergic to hygroscopic salts cannot be employed where such salts are used. Particularly disagreeable and noxious, in the way they affect mucous membranes, are wetting agents especially when they are sprinkled together with powder. While doing the sprinkling the workers should wear antidust masks and goggles. The most harmul is inhaling of the powder mixed with the wetting agent.

The pastes make slimy the surfaces of mine workings and of any objects which they cover. This must affect the accident rate, especially in inclined workings. The use of warning signs obviously does not solve the problem.

In addition to being noxious to their health the use of pastes is disagreeable to mine workers. Clothes permeated with pastes do not get dry, and this fact contributes a good deal to the irritation of the skin. Men who are engaged in working with pastes ought to wear rubber dresses or, everyday, fresh, dry working clothes. Rubber boots must be worn as leather boots become deformed under the influence of lye.

The corrosion influence of pastes is very strong. Often it becomes impossible to unscrew bolts in mechanical appliances. The pastes act destructively on machines, electrical installations, advancing supports, hydraulic props, cable joints, electric switches, etc. Therefore all mechanical and electrical appliances must be specially protected against getting into contact with pastes. In galleries in which trolley wire is installed pastes cannot be used at all for it is practically impossible to protect the trolley wire

from being pasted over when pasting the gallery's surfaces. Cables can withstand the action of pastes only when the cable sheath is in perfectly good condition.

As can be seen from the above remarks the range of the negative effects of hygroscopic salts, used on such a large scale in the Federal Republic of Germany, is rather wide.

8.8.7. The binding of coal dust on the floor

A restricted use of hygroscopic salts for binding coal dust deposited on the floors of workings presents considerably less difficulties. Naturally it does not protect the workings against the propagation of coal dust explosions. Considering, however, that the largest quantities of coal dust become accumulated on the floor the binding of it helps in protecting the workings. This method is employed mainly in galleries in which there is much coming and going of miners in order to prevent the raising to the air of very harmful mine dust.

The method discussed here consists in the scattering of $CaCl_2$ flakes on the floor in quantities amounting approximately to 5 kg/sq m. The $CaCl_2$ flakes absorb water from the air producing thereby a solution the concentration of which depends on the humidity of the air. The solution practically never dries up, the losses of it being accounted for chiefly by the fact that it soaks into the rock. In connection with this, the loss of $CaCl_2$ has to be made up by scattering, over a period of 3 to 9 months, of about 3 kg of flakes per 1 sq m. Coal dust, mine dust in general, becomes well bound through being mixed with the $CaCl_2$ solution as the result of the movement of workmen. In order to increase the wetting properties of $CaCl_2$ the spraying with water containing wetting agents can be used as a supplementary measure.

Instead of using $CaCl_2$ it is possible to pour over the floor waste lye obtained in the processing of potassium salts. This, of course, comes much cheaper.

In Polish mines the binding of coal dust on the floor is done on a very small scale on account of the high cost of $CaCl_2$.

8.9. THE DEGREE OF THE HAZARD OF COAL DUST EXPLOSIONS TO WHICH WORKINGS ARE EXPOSED BEYOND THE ZONE PROTECTED AGAINST THE PROPAGATION OF EXPLOSIONS

8.9.1. A general characteristic of investigations

According to regulations which are actually in force it is required that zones of only 200 m, in all directions from places at which explosions are likely to be initiated, ought to be protected against the propagation of explosions. It became very important, therefore, to investigate the hazard to which the workings are exposed beyond the protected zones.

In the workings in which coal dust deposits were examined the dusting with stone dust had not been required. In the examined workings incombustible solid matter in the dust was of the natural origin and, partly, represented the remainder of stone dust from the time when in the zones in question stone dusting had been required by regulations.

Investigations were carried out in dry haulage roadways.

The entire accumulations of the deposited dust were analyzed — that is, no samples were collected from separate layers but the entire dust accumulated in a working was examined.

Altogether 7170 m of haulage roadways were examined among them:

— 17 belt-conveyor roads of the total length of 560 m,

— 5 inclined planes with gravity loading of coal of the total length of 560 m,

— 6 flight conveyor roads of the total length of 640 m,

— 2 car haulage roadways of the total length of 370 m.

Twelve mines were covered by the investigations described here.

The dust collected from each working had been analyzed in respect of its physical and chemical properties and the quantity of mine dust per unit of volume of each working had been computed. This value was then converted to pure carbon substance q_c. On the basis of the analysis of the dust, making use of the author's formula given in Section 8.10, the content of incombustible solid matter n was determined sufficient to make the dust incapable of propagating an explosion with 30mPII used as the initiator in the easiest dispersion conditions. In all of the examined cases it was found that the actually established content of incombustible solid matter n had been lower than the computed value n_p which means that the examined mine dust was capable of propagating an explosion. On account of the fact that the hazard connected with dust deposits in the upper parts of workings is particularly serious, separate samples were collected from the floors, from the sidewalls, from the roof and roof bars. The last mentioned two kinds of samples were designated as roof samples.

A joint mean sample of the dust from the entire cross section of the working was also collected. Physical and chemical analyses were made of each of these four kinds of samples.

In consequence the following characteristics were separately determined:

— the dustiness of the working in terms of pure carbon substance q_c, kg/cu m,

Table 8.6

Results of the Examination of Coal Dust Deposits in the Typical Haulage Roads beyond the Zones in which, According to Regulations, Coal Dust Has to Be Protected (the Dustiness of the Working q_c Is Converted to Pure Carbon Substance)

The examined parameters of the explosibility of coal dust	Type of conveyor road			
	gravity loading	belt conveyor	flight conveyor	mining cars
1	2	3	4	5
Dustiness of the floor q_{cs}, kg/cu m:				
maximum	2.60	1.93	0.27	0.18
minimum	0.12	0.07	0.05	0.10
mean	1.20	0.63	0.20	0.11
Dustiness of sidewalls, q_{co}, kg/cu m:				
maximum	0.11	0.25	0.11	0.11
minimum	0.02	0.01	0.04	0.05
mean	0.08	0.06	0.06	0.08
Dustiness of the roof $q_{c,st}$, kg/cu m:				
maximum	0.15	0.05	0.02	0.003
minimum	0.05	0.02	0.01	—
mean	0.10	0.03	0.02	0.001
Dustiness of the whole working, $q_{c,calk}$, kg/cu m:				
maximum	2.99	2.32	0.52	0.20
minimum	0.22	0.15	0.12	0.11
mean	1.38	0.85	0.34	0.15
Mean contents of fraction <75 μm in the dust (fineness), d_m, %:				
from the floor	50.8	35.5	36.7	36.9
from the sidewalls	60.3	56.4	35.5	
from the roof	82.0	78.2	76.1	51.5
from the whole working	60.6	58.4	46.9	48.4
Mean content of incombustible solid matter in the dust, n, %:				
from the floor	23.7	24.3	34.6	39.3
from the sidewalls	24.9	27.2	30.6	75.3
from the roof	24.2	22.6	26.4	
from the whole working	24.8	25.2	31.5	66.7

— the fineness of the mine dust d_m as the content of the fraction < 75 μm, %,

— the mean content of incombustible solid matter n, %.

Only in the case of car haulage roadways the above far-going differentiation of dust deposits was renounced.

The results of these extensive investigations, carried out by Janota [98] and Pawlak [132] are presented in Table 8.6.

8.9.2. Inclined planes with gravity loading of coal

The highest dustiness, the mean value of the magnitude $q_{c,calk} = 1.38$ kg/cu m, was found in inclined planes with gravity loading of coal. The maximum value of $q_{c,calk}$ was as high as approximately 3 kg/cu m.

Likewise the highest roof dustiness, the mean value of $q_{c,st}$ being equal to 0.10 kg/cu m was found in the same inclined planes. The maximum value of $q_{c,st}$ amounted to 0.15 kg/cu m.

The fineness of the dust in these inclined planes was the highest, the mean value of $d_m = 60.6$ percent.

Very characteristically the mean fineness of the dust was the highest in the roof samples: $d_m = 82$ percent; it was lower on the sidewalls: $d_m = 60.3$ percent; and the lowest on the floor: $d_m = 50.8$ percent.

In spite of these differences between the values of d_m the fineness of the dust in all parts of the cross section of inclined planes was, generally, very high.

The mean content of incombustible solid matter n proved to be practically independent from the location of the dust in the cross section of the inclined planes and amounted to about 25 percent. This fact demonstrates that in the inclined planes pure coal dust is present — that is, a dust containing only the natural incombustible solid matter present in the coal extracted from the seam and derived from the crushed roof and floor substance.

It follows from the presented data that inclined planes with gravity loading of coal are exposed to a particularly serious hazard. The workings in question are the most difficult to protect against the dangerous coal dust.

Wherever local conditions permit coal dust deposits ought to be washed down from the upper parts of inclined planes with water jetted under pressure; and the points of discharge of the output into the inclined planes, as well as out of them, into the haulage facilities in the main roadways must be systematically sprayed with water.

Naturally the dusting with stone dust cannot be employed in such planes. The use of stone dust or water barriers is possible under condition

that the shelves or containers of such barriers will not be knocked off by the gravity loading of coal.

Inclined planes with gravity loading of coal cause also a far-going dustiness of the neighboring workings. Only under conditions of an exceptionally high natural humidity the inclined planes do not create a serious direct hazard.

Such inclined planes ought to be marked on the mine plans on which also the great hazard presented by them have to be signalized.

Apart from the washing down of coal dust, as mentioned already, the workings adjacent to the inclined planes should be protected by stone dust or water barriers and by zones dusted with stone dust to make its content in the mine dust equal to at least 80 percent.

It is necessary to remember that an explosion developed in such inclined planes acts as an exceptionally strong initiator capable of starting an explosion even in deposits of very wet coal dust.

8.9.3. Belt-conveyor roads

In belt-conveyor roads the mean dustiness expressed in terms of pure carbon dust, $q_{c,\,calk}$, was equal to 0.85 kg/cu m but locally it reached the value of 2.32 kg/cu m. Of course the highest dustiness was found on the floors, the mean $q_{cs} = 0.63$ kg/cu m but locally it amounted to more than 1.90 kg/cu m. The lowest dustiness was observed at the roof where the maximum $q_{c,st} = 0.05$ kg/cu m; the sidewalls were more dusty — the maximum $q_{co} = 0.25$ kg/cu m.

The fineness of the dust in the entire cross section of belt-conveyor roads, $d_m = 58.4$ percent, was almost equal to that found in inclined planes with gravity loading of coal. The fineness of the dust on the floor was lower, the mean value of $d_m = 35.5$ percent. In general, the fineness of the dust in belt-conveyor roads was found to be very close to the fineness of the dust in the workings with gravity loading of coal.

The mean content of incombustible solid matter n amounted, as in the case of inclined planes with gravity loading of coal, to about 25 percent.

Consequently the hazard of the propagation of coal dust explosions in belt-conveyor roads is considerable just slightly smaller than the same hazard in the inclined planes with gravity loading of coal. The hazard of coal dust explosions in belt-conveyor roads is widely known and has already been discussed in Section 6.2 in which special investigations have been described on the propagation of coal dust explosions in such roads.

The dusting of belt-conveyor roads with stone dust presents very great operational difficulties and the effects of it are small on account of

the intensive deposition of coal dust in these roads. The washing down of dust deposits is more difficult in belt-conveyor roads than it is in the inclined planes with gravity loading of coal. But the use of side barriers of stone dust, or water barriers, is indicated if the humidity conditions are adequate. In belt-conveyor roads the most suitable are distributed barriers (Sections 9.1.12.3 and 9.1.12.4).

Very good results are obtained in the reduction of the dustiness in belt-conveyor roads when the discharge and transfer points are sprayed with water.

When belt-conveyor roads are not protected by distributed barriers it is necessary that at least all workings connected with them should be protected by zones intensively dusted with stone dust up to the value of $n = 80$ percent and by ordinary barriers. Instead of the dusting with stone dust and using stone dust barriers, when the conditions in the roads are humid, the spraying with water and water barriers can be employed.

8.9.4. Flight conveyor roads

The dustiness of flight conveyor roads is distinctly lower than that of workings discussed in Sections 8.9.2 and 8.9.3, the mean value in them of $q_{cs} = 0.34$ kg/cu m reaching a maximum of 0.52 kg/cu m. Accordingly, the dustiness at the roof and of the sidewalls was also considerably lower.

The mean fineness was considerable and amounted to only slightly less than 50 percent.

The mean content of incombustible solid matter was only slightly higher than it was in the workings discussed previously: it exceeded but imperceptibly 30 percent.

Thus conditions in flight conveyor roads are also very dangerous though the danger is somewhat smaller.

As flight conveyor roads are not so dusty the fighting against the dust hazard is easier there. The use of the dusting with stone dust would be technically out of place, not to mention the operational difficulties. The most appropriate way of fighting against coal dust in flight conveyor roads is the washing down of the dust with water from the upper parts of these workings, and making the dust safe on the floor by spraying it with water. As in the case of inclined planes with gravity loading of coal, this is possible when the dust imbibes water. Dry coal dust, when it is washed off the floor, rises into the air and a part of it forms dangerous deposits in the upper parts of the working. In such conditions the most proper method is the employment of distributed barriers as in the case of belt-conveyor roads.

Apart from placing distributed barriers in such roads the spraying of transfer and discharge points with water is indicated. Flight conveyor roads very frequently cause the dustiness of neighboring workings. This necessitates the use of only such protective measures as have been discussed in Section 8.9.2.

8.9.5. Car haulage roads

The car haulage roads are dusty with coal dust to a much smaller extent, as a rule, than the haulage roads previously described. In the examined car haulage roads the mean dustiness amounted only to $q_{c,calk} = 0.15$ kg/cu m and attained locally a maximum not exceeding 0.2 kg/cu m. The fineness of the dust was rather high and the mean value of $d_m = 48.8$ percent. The content of incombustible solid matter was considerable the mean value of n being equal to 66 percent. This high content of incombustible solid matter was due to the dusting of the roads in question with stone dust.

The dust in car haulage roads was unquestionably much safer than that in workings discussed in previous sections, yet it was capable of propagating explosions. But in this case it was much easier to make the dust in question safe. As the dustiness was low and the value of n high the quantity of stone dust necessary to protect these workings against the propagation of a coal dust explosion was quite inconsiderable. When the conditions in these workings are humid both the workings and the cars with the extracted coal can be sprayed with water. In consequence of the spraying the dustiness in car haulage roadways can be reduced considerably.

8.9.6. General information concerning the hazard to which workings are exposed beyond the zones in which coal dust, according to regulations, has to be made incapable of propagating explosions

It is evident from the data included in Table 8.6 and discussed in Sections 8.9.2–8.9.5 that the workings, where the binding regulations do not univocally require any steps to be taken to make coal dust generally safe, are exposed to a very serious hazard if they are dry enough. As has been repeatedly pointed out before in such menacing situations, in which neither the dusting with stone dust nor the spraying with water are obligatory, the entire burden of protecting workings containing dangerous coal dust rests on the system of barriers. Many a disaster has been avoided through the use of barriers.

It ought to be explained here that the regulations in force until now, as a matter of fact, provide for the protection of workings which contain large accumulations of dangerous coal dust, wherever such accumulations appear, but the relevant provisions are expressed inadequately. Actually it is so that, once a coal dust explosion gets beyond the 200 m zone which has to be protected against the propagation of explosions, this explosion can develop over long distances and be a cause of a great disaster. A system of stone dust or water barriers, which limits the reach of the explosion even beyond the zones protected according to regulation requirements, can prevent such disasters.

8.10. GENERAL FORMULAS EXPRESSING CONDITIONS IN WHICH COAL DUST IS INCAPABLE OF PROPAGATING AN EXPLOSION

8.10.1. Introduction

As has already been explained the explosibility of coal dust — that is, the possibility of the propagation of its explosion, depends on several fundamental parameters of this dust.

The French investigators Taffanel and Audibert, in the period of years from 1921 to 1926, have dealt with the problem of expressing the explosibility of coal dust by an empirical formula [166]. The author of the present book also worked out an analogous empirical formula [20]. Though the author's formula, for conditions existing in Polish mines, gave results more consistent with the results of experiments than the formula of the French investigators, yet both formulas were admittedly based on a too scant number of experiments.

At any rate the works carried out in Poland during the period between the wars have clearly demonstrated the necessity of collecting very ample experimental data in order to be able to express mathematically, with a sufficient accuracy, the dependence of the explosibility of coal dust upon the basic parameters of this dust. It has been established also that, unfortunately, the actual state of knowledge does not permit to determine the sought for function on theoretical grounds only,

Through a period of 40 years not a single investigator attempted to find a general expression for the explosibility of coal dust on either theoretical or experimental grounds.

Not before 1968 the author of the present book published a simplified formula expressing the functional interdependence between the basic parameters of the coal dust explosibility [51], and in 1969 he published general formulas representing safety conditions for coal dust as regards the prop-

agation of explosions [57] which will be discussed further on in this chapter.

8.10.2. General comments concerning formulas expressing conditions in which coal dust is incapable of propagating an explosion

As the result of 2200 experiments carried out on a large scale 12 formulas were ultimately worked out representing the dependence of the explosibility of coal dust upon: the content of volatile matter V, the fineness d, the content of incombustible solid matter n, the content of free water W_k. These formulas were worked out separately for the initiator 30mPII and for the initiator 50 cu m CH_4 (that is, for the explosive mixture of methane and air containing approximately 9.5 percent of CH_4).

For each of the above two initiators separate formulas were elaborated in respect of the easiest and the most difficult dispersion conditions. In addition, simplified formulas were derived in order to facilitate computations. Ultimately, as many as 12 formulas in question were worked out which appeared in the publication [57].

By using these formulas, on the basis of physicochemical analyses of the mine dust, it can be determined whether the dust contains a sufficient quantity of incombustible solid matter or of free water to be safe as regards the propagation of an explosion.

When reference is made to the dust being safe as regards the propagation of an explosion it means that a possible explosion can develop only over a distance shorter than 200 m.

Of the greatest practical value is the formula worked out for the initiator 30 mPII in respect of the easiest dispersion conditions. This formula is valid for the most dangerous conditions a given coal dust might fall in with in practice. The use of this formula, therefore, ensures the most effective safety coefficient in accordance with the general spirit of safety regulations in mines.

Likewise of a considerable practical importance is the formula worked out for the initiator 50 cu m CH_4 in respect of the easiest dispersion conditions.

The explosion initiator 50 cu m CH_4, being an explosive mixture of methane, is somewhat weaker than the explosion of very dangerous coal dust covering a zone of 30 m — that is, than the initiator 30mPII. However, taking into consideration the fact that methane explosions are the most classical initiators of coal dust explosions, the use of this formula is also well founded.

Taking advantage of the very wide extent of investigations on the explosibility of coal dust carrried out in the *EM Barbara*, formulas were

also worked out for both above mentioned initiators but, as has been mentioned already, in respect of the most difficult dispersion — that is, for conditions in which it is assumed that the dangerous deposits of coal dust are situated only on the floor. These formulas cannot be made use of in practice, as often as those previously discussed, but they are valuable for comparative purposes showing how great is the influence of dispersion conditions upon the explosibility of coal dust. The formulas in question can be used in such exceptional cases in which it is practically impossible to perceive coal dust deposits in the upper parts of workings while the dust is accumulated on the floor, for instance, when dust deposits are carefully washed down by streams of water from the sidewalls and the upper parts of a working so that the entire quantity of it accumulates on the floor.

All these formulas are based on a mass of experimental data the collection of which is the outcome of a very expensive work continued more than a quarter of a century. Taking this into account it has been decided to frame the derived formulas broadly in order to make the most of the long drawn work and considerable expense devoted to the study in the *EM Barbara* of the problem of the explosibility of coal dust.

Since the results of investigations now presented concern the quantitative relations between incombustible solid matter in a safe coal dust, jointly with water contained in the dust, it becomes necessary to introduce new symbols to denote the contents of incombustible matter. The symbol S, serving until now to denote the empirical limit of the content of incombustible matter in dry dust, will not be used in the further text. In scientific literature it is a quite normal and accepted custom to denote the limit values of variables and the facultative values of the same variables by different symbols. The limit values S served only to educe the examined relations between the incombustible substances in the dust regarded as safe. However, when any given dust is being examined with regard to its capability of propagating an explosion, the limit values S do not come into account because they are not known in advance. In fact the analysis of the mine dust supplies facultative values of incombustible substances which a dust sample might contain and in order to differentiate these values from the limit values S, different symbols are adopted for the new variables. Besides, in this case two kinds of symbols must be distinguished: one kind denotes the empirical contents of incombustible matter in a random sample of the dust, and the second kind denotes quantities derived from the relevant regression equations representing the expected minimal values of incombustible matter content in the dust making it safe as regards the propagation of an explosion. It follows that even this last mentioned magnitude is not identical with the value of S.

In the formulas discussed here the following designations are used the accurate knowledge and use of which is necessary for the understanding of the formulas as well as for utilizing them:

V — the content of volatile matter in the d.a.f. carbon substance, %,

d_m — the content of the dust fraction < 75 μm in the mine coal dust, %,

d — the content of the dust fraction < 75 μm in the pure coal dust, %,

n — the content of incombustible solid matter in the mine dust — that is, in the dust containing free water, %,

n_0 — the content of incombustible solid matter in the dry dust (not containing free water), %,

n_{0p} — the content of incombustible solid matter in the dry dust in conditions of the easiest dispersion sufficient to protect against the propagation of an explosion according to the regression equation, %,

n_p — the content of incombustible solid matter in the mine dust (i.e., in the dust containing free water) sufficient to prevent the propagation of an explosion according to the regression equation, %,

n_{0u} — the content of incombustible solid matter in the dry coal dust sufficient to prevent the propagation of an explosion according to the simplified regression equation, %,

W_k — the content of free water in the dust, %,

W_p — the content of free water sufficient to prevent the propagation of an explosion according to the regression equation, %,

n'_{0p} — the content of incombustible solid matter in the dry dust sufficient to prevent the propagation of an explosion in the most difficult dispersion conditions according to the regression equation, %.

The term: **the mining coal dust** is used to denote the natural dust present in a given working, a sample of which is collected to make physicochemical analyses of it.

The term **pure coal dust** denotes the dust derived from the comminution of the coal from the seam — that is, the dust containing only the natural incombustible solid matter (called the ash) and hygroscopic water. The pure dust does not contain limestone dust used for dusting the workings or stone dust originating from the crushing of either the roof or floor rocks.

The term: **free water** denotes the transitory humidity called also the mine humidity which disappears from the coal in a room temperature in the average dry conditions of a laboratory.

Dry dust is the term used to denote mine dust, dried in conditions described above — that is, containing no free water.

The necessity ought to be underlined of denoting very accurately the analytical values mentioned above found in the dry dust or in the mine

dust containing free water, in other words, in the dust actually present in a given working.

In very frequent cases mine dust contains quite insignificant quantities of free water — that is, < 4 percent. In such cases it is permissible, and even indicated for the sake of simplicity, to leave out of account this water content and to regard the given dust as dry.

The formulas given further on in this chapter make it possible to find:

— the content of incombustible solid matter n_p sufficient to make the dust safe as regards the propagation of an explosion when the dusting with stone dust is used to this end, or

— the content of free water W_p sufficient to make coal dust safe against the propagation of an explosion when the spraying with water is used to attain this end, or when the mine dust is naturally very humid.

8.10.3. The accuracy of the formulas when compared with the results of experiments

The question of the accuracy of the values computed according to formulas, when compared with the values established is presented in the publication [57]. The accuracy is quite sufficient for practical purposes.

For all the educed formulas, from (8.13) to (8.24), it was established that:

the random mean errors in determining the value of n_p reach 3.5 percent,

the random mean errors in determining the value of W_p reach 2 percent.

This can be expressed by the mean tolerance limit

$$n_p - 3.5 < n_d < n_p + 3.5$$

$$W_p - 2 < W_d < W_p + 2$$

where n_d and W_d represent the values which are expected to be found as the result of experiments.

It follows from the above that, on the average, at least 70 percent of the real values of n_d and W_d are comprised within the given limits.

The multiple correlation coefficients oscillate between 0.97 and 0.98 and are therefore sufficiently high to confirm unreservedly the very good conformity of the formulated regression equations with the results of experiments.

8.10.4. Formulas for the initiator 30 mPII and the most favorable dispersion conditions

For the initiator 30mPII and the easiest dispersion conditions

$$n_p = n_{0p} - 1.71 W_k \tag{8.13}$$

$$W_p = 0.58(n_{0p} - n) \tag{8.14}$$

The value of n_{0p} in the formulas (8.13) and (8.14) is ascertained by solving the following equation

$$n_{0p} = 100 \frac{d + 113.34 - (0.268d + 20.539)V + (0.014d + 0.957)V^2}{d + 138.35 - (0.268d + 26.960)V + (0.014d + 1.365)V^2} \tag{8.15}$$

The formula (8.13) is used in such cases in which workings are dusted with limestone dust in order to make coal dust safe.

The formula (8.14) is used when workings are sprayed with water in order to make coal dust safe.

The formulas (8.13) and (8.14) may be used when the content of volatile matter V is comprised within the limits from 13.3 to 45 percent.

Normally the analyses of the dust dried in the air are made — that is, when it is deprived of free water W_k. In such a dust the content of incombustible solid matter is denoted by the symbol n_0.

In the formula (8.14) there appears the magnitude n — that is, the content of incombustible solid matter in the undried mine dust, in other words, in the dust containing free water.

Knowing the values of n_0 and W_k the value of n is ascertained by using the elementary formula

$$n = n_0(1 - 0.01W_k) \tag{8.16}$$

On account of the fact that in the formula (8.15) the fineness of the dust d refers to pure coal dust it is necessary to ascertain the magnitude of d on the basis of the value of d_m determined experimentally by using the formula

$$d = \frac{100(d_m - 0.6n_0)}{100 - n_0} \tag{8.17}$$

Naturally when using the formula (8.15) it is necessary to know the content of volatile matter V in the coal of the given seam.

In order to establish whether a given mine dust is capable of propagating an explosion a determinant sample of the dust from the working in question ought to be collected and the content in it of free water W_k ascertained. Next, the dust sample ought to be dried in the air under the normal laboratory conditions and then sifted through a sieve of a 1 mm mesh.

In the sifted dust (in the fraction < 1 mm), through further sifting, the content ought to be fixed of the fraction < 75 μm — that is, d_m. Also in the sifted dust representing the fraction < 1 mm the content should be ascertained of incombustible matter n_0. On the basis of the obtained values of d_m and n_0 the value of d is fixed by using the formula (8.17) and then the value of n_{0p} by using formula (8.15).

When the content of free water in the dust W_k is low, for example, lower than 4 percent, in the fight against the explosibility of coal dust the dusting of workings with limestone dust should be used. In this connection the computed value of n_{0p} should be compared with the value of n_0 found for the collected dust sample; if n_{0p} is higher than n_0 the dust in question is capable of propagating an explosion. Therefore, the quantity of limestone dust should be added to it to make the content of incombustible matter in the dust at least equal to n_{0p}.

However, if one wished to take into account the influence of even a low content of free water W_k he would have to ascertain the value of n_p having found previously the value of n_{0p} by using the formula (8.13).

The quantity of limestone dust, which ought to be added per weight unit of a given dust in order to bring the content of incombustible matter in the dust at least to the value of n_{0p}, can be ascertained by using the formula for the weight unit coefficient α

$$\alpha = \frac{n_{0p} - n_0}{100 - n_{0p}} \tag{8.18}$$

If the analysis of the collected sample shows that $n_{0p} \leqslant n_0$ it means that the dust in question is not capable of propagating an explosion.

The above remarks refer to a situation in which the content of free water in the dust is low ($<$ than 4 percent) and because of that this content is left out of account the dust being regarded as dry.

When, however, a given dust possesses a higher content of free water, for example, $W_k = 7$ percent then, in order to ascertain the content of incombustible solid matter in the dust in question, sufficient to prevent the propagation of an explosion, it is necessary, having established first the value of n_{0p}, to calculate the value of n_p by using the formula (8.13).

If it is found that the value of n_p so obtained is higher than the value of n the dust in question is capable of propagating an explosion and, to make it safe, it is necessary to add a quantity of limestone dust which will increase the content of incombustible solid matter at least to the value of n_p. In a case of this kind the weight unit coefficient α is found by using the formula

$$\alpha = \frac{n_p - n}{100 - n_{0p}} \tag{8.19}$$

When dealing with dry dust ($W_k \cong 0$) — that is, when low content of free water is not taken into account the formulas (8.18) and (8.19) become equivalent since then

$$n_p = n_{0p} \quad \text{and} \quad n = n_0$$

The above explanations refer to cases in which the dusting with limestone dust is used for combating the explosibility of coal dust. In the cases in which workings are sprayed with water, this method being used when the natural dust imbibes water thanks to its high natural humidity, in order to ascertain the content of water W_p sufficient to make the dust safe as regards the propagation of an explosion the formula (8.14) ought to be used.

In order to establish whether a given mine dust has a sufficient content of free water W_k it is necessary — having collected a determinant sample of the dust — to make a physical and chemical analysis of it for finding the values of: W_k, n_0, n and d_m. The analysis has to be made in the manner described previously.

The next step is to find the value of n_{0p} by using the formula (8.15) and then to find the value of W_p according to the formula (8.14).

When $W_p > W_k$ the given dust is capable of propagating an explosion. With $W_p \leqslant W_k$ the content of free water makes the given dust safe.

When $W_p > W_k$ the content of water in the dust ought to be increased at least to the value of W_p. To this end, per weight unit of the given dust a quantity of water ought to be added obtained from the formula for the weight unit coefficient β

$$\beta = \frac{n_p - n}{100q - n_{0p}} \tag{8.20}$$

where q denotes a coefficient computed from the formula given in the publication [57].

The value of q for the easiest dispersion conditions amounts to about 1.7 and for the most difficult dispersion conditions to about 1.6; q is a coefficient which appears with the variable W_k in equations (8.13), (8.23), (8.25), (8.28) and (8.32); the values of q, as depending upon the conditions of dispersion and upon the initiator, are given in Table 8.7.

The best illustration of the way in which the formulas discussed here may be used will be found in the following examples:

Example 1

The results obtained through the analyses of the coal from the given seam, and of the dust sample, are as follows:

$$V = 37\%; \quad d_m = 40\%; \quad n_0 = 60\%; \quad W_k = 5\%$$

Making use of the formula (8.17) the value of d is found to equal 10 percent and from the formula (8.15) it is found that $n_{0p} = 68.9$ percent.

As it is seen from the comparison of n_{0p} with n_0, $n_{0p} > n_0$ which means that the dust is capable of propagating explosions and that the content of incombustible solid matter in it ought to be increased by dusting the workings with limestone dust.

Table 8.7

Values of the Coefficient q Appearing in Equations (8.13), (8.23), (8.25), (8.28), (8.32) Depending on the Dispersion Conditions and on the Initiators Used

Initiator	Dispersion conditions	
	easiest	most difficult
For unsimplified formulas		
30 mPII	1.71	1.56
50 cu m CH_4	1.63	2.16
For simplified formulas		
30 mPII	1.76	1.56
50 cu m CH_4	1.72	2.16

If one leaves out of account the presence in the dust of free water, the quantity of limestone dust to be added to the dust to increase its content n_0 to the level of $n_{0p} = 68.9$ percent, can be determined from the formula (8.18) for the weight unit coefficient α.

The value of α, which will be found to be $\alpha = 0.3$, indicates that 0.3 kg of limestone dust have to be added to 1 kg of the given dust.

If it is desired to take into account also the influence of free water it will be necessary to use the formulas (8.13) and (8.16) for determining the value of $n_p = 60.3$ percent, the symbol n_p representing the content of incombustible solid matter in the wet coal dust (W_k being equal to 5 percent) sufficient as a protection against the propagation of explosions. In order to establish whether the value of $n_p = 60.3$ percent is actually sufficient to make the given dust safe, the above value must be compared with the value of n in the given dust — that is, with the content of incombustible solid matter computed for wet dust (with $W_k = 5$ percent). Using the formula (8.16) it is found that $n = 57$ percent.

Comparing the values of n_p and n it is seen that $n_p > n$ which means that the dust, with the free water contained in it taken into account, still remains capable to propagate explosions.

In order to determine the quantity of limestone dust which ought to be added to the given dust, taking into account its content of water, the formula (8.19) must be used for the weight unit coefficient α. The value of α is found to be $\cong 0.11$.

Example 2

The results obtained through the analyses of the coal from the given seam, and of the dust sample are as follows:

$$V = 40\%; \quad d_m = 50\%; \quad n_0 = 20\%; \quad W_k = 10\%$$

When the content of water $W_k = 10$ percent it is possible, as a rule, to use the spraying with water or the dusting with limestone dust in order to make the dust safe. Both methods, therefore, are dealt with here.

Making use of the formulas (8.13) to (8.17) it is found that

$$d = 47.5\%; \quad n_{0p} = 77.2\%; \quad n_p = 60.1\%; \quad n = 18\%; \quad W_p = 34.3\%$$

The comparison of the above computed values with the values found from the analysis of the dust sample shows that the dust in question contains insufficient quantities of incombustible solid matter as well as of water to make it safe as regards the propagation of an explosion since $n_{0p} > n_0$, $n_p > n$ and $W_p > W_k$.

If the spraying with water is to be used to make this dust safe the least quantity of water which ought to be added to the dust has to be computed by determining the weight unit coefficient β from the formula (8.20); in this case $\beta = 0.5$ which means that to every kg of the given dust at least 0.5 kg of water should be added.

When the method of water spraying is used it is always necessary to add more water than the quantity indicated by the established value of β since, in the conditions existing in mines, the water used for spraying is partly carried away by the air current, and partly evaporates and covers the surface of the working, the support, the piping, etc.

When, to make the dust in question safe, the dusting with stone dust is used, the quantity of limestone dust which should be added to this dust has to be computed by finding the weight unit coefficient a according to the formula (8.19), the value of α in this case being equal to 1.9.

Again when the dusting with limestone dust is employed more limestone dust should be added than the quantity computed on the basis of the value of a, on account of the unavoidable losses of this dust which, however, are smaller than the losses of water.

8.10.5. Simplified formulas for the initiator 30mPII and the most favorable dispersion conditions

The formula (8.15) for computing the value of n_{0p}, being relatively a complicated one, simplified formulas were worked out through the approximation of the relevant curves by straight lines. As a result the formula (8.21) has been obtained for the contents of volatile matter $V \geqslant \geqslant 20$ percent and the formula (8.22) for the contents of volatile matter $V < 20$ percent.

In these formulas the symbols n_{0pu}, n_{pu} and W_{pu} are used to denote the magnitudes n_{0p}, n_p and W_p when they are computed according to simplified formulas.

For $V \geqslant 20\%$

$$n_{0pu} = 100\frac{85+d-0.6V}{150+d-1.5V} \tag{8.21}$$

For $V < 20\%$

$$n_{0pu} = 100\frac{-4V^2+(d+48)V-10d+800}{(d-177)V-10d+3900} \tag{8.22}$$

$$n_{pu} = n_{0pu} - 1.76W_k \tag{8.23}$$

$$W_{pu} = 0.57(n_{0pu} - n) \tag{8.24}$$

The way in which the above formulas should be used are illustrated hereunder on the examples given in Section 8.10.4.

Example 1 (the data as in Section 8.10.4)

Using the formulas (8.21), (8.23), (8.24) it is found that

$$d = 10\%; \quad n_{0pu} = 69.7\%; \quad n_{pu} = 60.9\%; \quad n = 57\%; \quad W_{pu} = 7.2\%$$

The comparison of the above values with the values computed according to the full formulas given in Section 8.10.4 shows that the difference is very small between the values n_{0p}, n_p, W_p and the values n_{0pu}, n_{pu} and W_{pu}, respectively.

When free water is disregarded the weight unit coefficient

$$\alpha = \frac{n_{0pu}-n_0}{100-n_{0pu}} \cong 0.3$$

this magnitude being identical with that established according to the full formulas. Consequently, the small differences in the computed values of n_{0pu}, n_{pu} and W_{pu} do not affect in any perceptible way the quantity of limestone dust which ought to be added to the dust to make it safe with regard to the propagation of an explosion.

For the sake of precision it ought to be made clear that the weight

unit coefficients α and β have to be found, of course, according to the formulas (8.18), (8.19) and (8.20) given in Section 8.10.4.

Example 2 (the data as in Section 8.10.4)

Making use of the simplified formulas it is found that

$$d = 47.5\%; \quad n_{0pu} = 78.9; \quad n_{pu} = 61.3\%; \quad n = 18\%; \quad W_{pu} = 34.7\%$$

The comparison of the values found, according to the full formulas, of n_{0p}, n_p, and W_p with the values of n_{0pu}, n_{pu} and W_{pu} shows, in this case also, very insignificant differences between the respective values.

The weight unit coefficient α by which the quantity is determined of limestone dust to be added to the given dust, taking into account the water content $W_k = 10$ percent, amounts to

$$\alpha = \frac{n_{pu} - n}{100 - n_{0pu}} \cong 2.05$$

Similarly the weight unit coefficient β by which the quantity of water is determined to be added to the given dust to make it safe through water spraying amounts to

$$\beta = \frac{n_{pu} - n}{100 \cdot 1.76 - n_{0pu}} \cong 0.45$$

Comparing the values of α and β, found from the full formulas, with the relevant values found from the simplified formulas slight divergences in this case are ascertained. Namely, the value of α formerly amounted to approximately 1.9 and the value of β to about 0.5. These differences are of small consequence from the practical point of view.

Thus the simplified formulas may be used in practice without any fear of committing an inaccuracy of a real importance to the task of making coal dust safe with regard to the propagation of an explosion.

8.10.6. Formulas for the initiator 50 cu m CH_4 and the most favorable dispersion conditions

For the initiator 50 cu m CH_4 and the easiest dispersion conditions

$$n_p = n_{0p} - 1.63W_k \tag{8.25}$$

$$W_p = 0.61(n_{0p} - n) \tag{8.26}$$

The value n_{0p} appearing in the formulas (8.25) and (8.26) amounts to

$$n_{0p} = 100\,\frac{d - 44.87 - (0.1107d - 2.9473)V + (0.003117d - 0.008139)V^2}{d - 53.11 - (0.1107d - 3.0852)V + (0.003117d + 0.024254)V^2} \tag{8.27}$$

The formula (8.25) is used in the cases in which the workings are dusted with stone dust and the formula (8.26) in the cases of the workings

sprayed with water. The formulas (8.25) and (8.26) may be used where coal dust contains from 16 to 45 percent of volatile matter V. The way in which these formulas ought to be used is quite analogous to that described in Section 8.10.4.

In order to compare the influence of the different initiators on the explosibility of coal dust relevant computations were made for the examples 1 and 2 given in Section 8.10.4.

Example 1 (data as given in Section 8.10.4)

Using formulas (8.25), (8.26), (8.27) and formulas (8.16), (8.17) we get

$$d = 10\%; \quad n_{0p} = 61.1\%; \quad n_p = 53.0\%; \quad n = 57\%; \quad W_p = 2.5\%$$

Comparing the values of n_{0p} and of n_0 we find that the value of n_{0p} is only very slightly higher than that of n_0 so that the examined dust may be regarded as incapable of propagating an explosion, the more so since in calculating the value of n_{0p} the water content in the dust had been left out of account. The safeness of the dust is also confirmed by the value of W_p which indicates that even a 2.5 percent content of free water would make the dust in question unable to propagate an explosion when actually the examined dust contains $W = 5$ percent.

The same dust, as was explained in Section 8.10.4, was capable of propagating an explosion when the 30mPII initiator had been used.

Considering that the value n_{0p} is slightly higher than the value n_0 a very small quantity of limestone should be added to the dust in question in order to fulfil the conditions of the formula in which the content of free water in the examined dust had been disregarded. The weight unit coefficient α in this case is found to be approximately 0.03.

The comparison thus carried out between the initiators used shows clearly that the 30mPII initiator is stronger than the 50 cu m CH_4 initiator which agrees completely with the results of extensive investigations carried out in the *EM Barbara* on the influence of initiators upon the explosibility of coal dust.

Similarly in order to compare the influence of the two initiators computations were made with the use of the formulas (8.25), (8.26) and (8.27) in reference to Example 2 as given in Section 8.10.4.

Example 2 (data as given in Section 8.10.4)

Using formulas (8.25), (8.26), (8.27) and taking into account the free water content $W_k = 10$ percent we find

$$d = 47.5\%; \quad n_{0p} = 73.2\%; \quad n_p = 56.9\%; \quad n = 18\%; \quad W_p = 33.7\%$$

As can be seen from the results obtained the coal dust deposited in the examined working is capable of propagating an explosion as $W_p > W_k$. If the dusting with limestone dust is to be used to make the coal dust safe,

to every weight unit of the dust, taking into account water content W_k = = 10 percent, the quantity of limestone dust ought to be added determined on the basis of the weight unit coefficient $\alpha \cong 1.5$.

If the coal dust is to be made safe by the spraying with water, to every weight unit of the dust the quantity of water should be added determined on the basis of the weight unit coefficient $\beta \cong 0.44$.

Comparing the present solution with the solution given in Example 2 in Section 8.10.4 — that is, with reference to the 30mPII initiator, it can be seen that the values of n_{0p}, n_p and W_p are, in the case of the 50 cu m CH_4 initiator lower than in the case of the 30mPII initiator. The difference can be seen in the weight unit coefficient α for the 50 cu m CH_4 initiator being lower than for the 30mPII initiator by about 0.4. The weight unit coefficients β differ by about 0.06.

Obviously these differences are caused by the 30mPII initiator being stronger than the 50 cu m CH_4 initiator a fact which exerts an influence upon the explosibility of coal dust designated by the quantity of limestone dust or water sufficient to make the given coal dust safe with regard to the propagation of an explosion.

8.10.7. Formulas for the initiator 30mPII and the most difficult dispersion conditions

For the 30mPII initiator and the most difficult dispersion conditions

$$n_p = 0.93n_{0p} - 1.56W_k \tag{8.28}$$

$$W_p = 0.62(n_{0p} - n) - 3 \tag{8.29}$$

$$n'_{0p} = 0.93n_{0p} \tag{8.30}$$

The value of n_{0p} appearing in formulas (8.28), (8.29), (8.30) is computed by using the following equation

$$n_{0p} = 100\frac{d - 44.87 - (0.1107d - 2.9473)V + (0.00311d - 0.008139)V^2}{d - 53.11 - (0.1107d - 3.0852)V + (0.003117d + 0.024254)V^2} \tag{8.31}$$

The symbol n'_{0p} in equation (8.30) denotes the content of incombustible solid matter in the dry dust sufficient as a protection against the propagation of a dust explosion in the most difficult dispersion conditions — that is, when the dust is deposited on the floor only. It should be remembered that the symbol n_{0p} was used to denote the analogous content of incombustible solid matter but in the easiest dispersion conditions.

The formulas presented above may be used for the range of the volatile matter content V from 17 to 45 percent.

Using these formulas computations were made for the two examples given in Section 8.10.4.

Example 1 (data as given in Section 8.10.4)

Using formulas (8.28), (8.29), (8.30) we find

$$d = 10\%;\quad n_{0p} = 61.1\%;\quad n'_{0p} = 56.8\%;\quad n_p = 49.0\%;\quad n = 57\%;\quad W_p = 0\%$$

The value of W_p computed by using formula (8.2) amounts to: $W_p \cong \cong -0.5$. As the inequality has to be $W_p \geqslant 0$, the result obtained has been rounded off to read: $W_p = 0$.

Formulas (8.28), (8.29), (8.30) are approximate and, therefore, the possibility exists of getting a negative value if the computed value is close to zero.

It follows from the comparison of the computed values with those found through the analysis that the coal dust in question, in the conditions of the most difficult dispersion, is not able to propagate an explosion since $n'_{0p} < n_0$, and $W_p < W_k$.

Example 2 (data as given in Section 8.10.4)

Using formulas (8.28), (8.29), (8.30) and taking into account free water content in the dust $W_k = 10$ percent we get

$$d = 47.5\%;\ n_{0p} = 73.2\%;\ n'_{0p} = 68.0\%;\ n_p = 52.5\%;\ n = 18\%;\ W_p = 31.2\%$$

As can be seen from the comparison of the computed values with the concrete data the dust is capable of propagating an explosion since $W_p > W_k$ and, besides, $n_p > n$.

If the dusting with limestone dust is to be used to make the coal dust safe the weight unit coefficient α, when the water content of the dust $W_k = 10$ percent is taken into account, amounts to

$$\alpha = \frac{n_p - n}{100 - n'_{0p}} = 1.1$$

When the dust is to be make safe through the spraying with water the weight unit coefficient

$$\beta = \frac{n_p - n}{100 \cdot 1.56 - n'_{0p}} = 0.4$$

By comparing the above values with the values of α and β found for the easiest dispersion conditions (Section 8.10.4) we can see, naturally, that to make the same dust safe in the most difficult dispersion conditions considerably smaller quantities of limestone dust or water are necessary.

8.10.8. Formulas for the initiator 50 cu m CH_4 and the most difficult dispersion conditions

For the 50 cu m CH_4 initiator and the most difficult dispersion conditions

$$n_p = 1.71n_{0p} - 2.16W_k - 54.3 \quad (8.32)$$

$$W_p = 0.79n_{0p} - 0.45n - 25 \quad (8.33)$$

$$n'_{0p} = 1.71n_{0p} - 54.3 \quad (8.34)$$

The value of n_{0p} is found by using formula (8.31). The formulas presented here may be used for the range of the volatile matter content V from 17 to 45 percent.

Using formulas (8.32), (8.33), (8.34) the examples 1 and 2 — given in Section 8.10.4 — were solved.

Example 1 was solved exclusively for the purpose of getting comparative values since there was no doubt that the dust in question is not capable of propagating an explosion with the 50 cu m CH_4 initiator in the most difficult dispersion conditions, considering that it proved to be unable to propagate an explosion already with the 30mPII initiator.

Example 1 (data as given in Section 8.10.4)

Using formulas (8.32), (8.33), (8.34) and leaving out of account the free water content $W_k = 5$ percent, we find

$$d = 10\%; \quad n_{0p} = 61.1\%; \quad n'_{0p} = 50.2\%$$

Naturally the computed values confirm the inability of the dust to propagate an explosion since $n_0 = 60$ percent $> n_{0p} = 50.2$ percent.

Example 2 (data as given in Section 8.10.4)

Using formulas (8.32), (8.33), (8.34) and taking into account the content of free water $W_k = 10$ percent we get

$$d = 47.5\%; \quad n_{0p} = 73.2\% \quad n'_{0p} = 70.9\%; \quad n_p = 49.3\% \quad n = 18\% \quad W_p = 24.7\%$$

By comparing the computed values with the concrete data one finds that the dust is capable of propagating an explosion since $n_p > n$ and $W_p > W_k$.

If the dusting with stone dust is to be used to make the coal dust safe the weight unit coefficient

$$\alpha = \frac{n_p - n}{100 - n'_{0p}} \cong 1.08$$

In the case when the spraying with water is used to make the dust safe the weight unit coefficient

$$\beta = \frac{n_p - n}{100 \cdot 2.16 - n'_{0p}} \cong 0.22$$

The above values of α and β are the lowest of all computed so far in reference to Example 2. This is natural considering that the explosibility of coal dust — in the different conditions for which the same weight unit

coefficients had been computed — happens to be the lowest under the most difficult dispersion conditions and with the use of the 50 cu m CH_4 initiator.

8.11. NOMOGRAMS FOR FINDING THE CONTENT OF INCOMBUSTIBLE SOLID MATTER AND OF FREE WATER IN BITUMINOUS COAL DUST SUFFICIENT TO MAKE A GIVEN TYPE OF DUST SAFE AS REGARDS THE PROPAGATION OF EXPLOSIONS

8.11.1. General information

Formulas given in Section 8.10 are based on the results of many years' investigation work. They are to serve as a means of utilizing in practice the results of these investigations. The use of these formulas, however, necessitates relatively toilsome calculations. Even in the case of simplified formulas calculations, naturally, cannot be avoided and therefore a possibility arises of committing errors now and then.

The use of the formulas, as has been explained in Section 8.10, becomes somewhat complicated through the fact that the fineness of the dust given in them refers to the pure coal dust primarily utilized in the tests.

In the dust samples collected in a mine the fineness d_m is determined by sifting the dust through a sieve of a 75 μm mesh. Such a dust usually represents a mixture of pure coal dust with limestone dust. It is, therefore, necessary, when using the formulas mentioned above, to establish previously the degree of the fineness of pure coal dust according of formula (8.17) as explained in Section 8.10.

In order to make the use of the fomulas as easy as possible complicated calculations were carried out which led to the elaboration of nomograms eliminating entirely the need of toilsome calculations on the part of those who use the nomograms.

The working out of the nomograms has been a very laborious task; the course of the relevant calculations is left entirely out of this book.

To be able to make use of the nomograms it is only necessary to have the results of the analyses of the mine dust samples collected, and the analysis of the coal samples taken from the seam. These analyses are elementarily simple and should supply the same data as those that are indispensable for the use of formulas discussed in Section 8.10 (see Sections 8.10.2 to 8.10.4).

The nomograms were worked out for all formulas given in Section 8.10.

The nomogram for the 30mPII and the easiest dispersion conditions should become the most widely used one. For, in practice, one must consider the possibility of having to deal with the strongest explosion initiators and with dispersion conditions most favorable to the development of explosions. The use of this nomogram, described in the next section, ensures an adequate safety margin in the evaluation of the ability of the dust to propagate an explosion, as well as in the calculation of the necessary limestone dust or water content to make the dust safe.

It should be very strongly emphasized that the elementary condition of getting reliable results from the use of formulas described in Section 8.10, or of the nomograms described in the present section, is a proper collection of a representative sample of mine dust from a given working.

If the collection of the sample is done improperly — that is, if the act itself of collecting the sample happens to have been encumbered with a serious fault it would be impossible to give the correct definition of the explosibility of the dust, or correctly to determine the supplementary dusting with limestone dust or the supplementary spraying with water of the dust in question in order to make it safe. The situation of this kind is heavy with a menace of the most disastrous consequences. The higher supervisory personnel of the mine, as well as the mining authorities, would be led to belive that the danger of a coal dust explosion in the working in question was correctly prevented, while in actual fact no such prevention had been achieved. Of course it could also happen that the way in which the sample was collected would affect the results of the analysis so as to create ultimately a wider margin of safety, but the experience of many years, concerning the way in which various samples are collected in mines, justifies the fear that the collection of samples will be done rather in a manner tending to create the least possible inconvenience to the mine in connection with the problem of making the dust safe with regard to the propagation of an explosion.

In the nomograms the same symbols are used as in the formulas described in Section 8.10. When discussing the nomograms, therefore, these symbols will not be explained again.

Each of the nomograms consists of seven scaled lines designated by symbols d_m, n_0, d, n_{0p}, V, n, W.

The meaning of the symbols were given in Section 8.10.2 and they will be repeated in the examples presented here in connection with the discussion of particular nomograms.

8.11.2. A nomogram for the initiator 30mPII and the easiest dispersion conditions

The nomogram shown in Fig. 8.24 is based on formulas (8.13), (8.14),

(8.16) and (8.17) presented in Section 8.10.4. The use of the nomogram is very simple. You get the answer to the question whether a given mine dust is capable of propagating an explosion when the very strong 30mPII iniatiator is used in the easiest conditions of the dispersion of the dust.

If the examined coal dust is dry — that is, when it contains < 4 percent of free water W_k or when the presence of free water in the dust is altogether left out of account we get the answer to our question by comparing the content of incombustible solid matter in the dry dust n_0 as found through the analysis of the dust with the required content of incombustible solid matter n_{0p} found with the aid of the nomogram.

When $n_0 < n_{0p}$ then the dust is capable of propagating an explosion and the content in it of limestone dust ought to be supplemented at least to the value of n_{op}.

The quantity of limestone dust which ought to be added to the examined dust is found by using formula (8.18) for the weight unit coefficient α. Formula (8.18) is used in the cases in which the free water W_k in the examined dust is left out of account — that is, when the content of free water is lower than 4 percent or when this content varies in a way which shows that it should not be regarded as a constant factor impeding the propagation of an explosion. When the influence of free water W_k is taken into consideration (in the working in question the conditions of humidity being constant) the value of the weight unit coefficient α has to be computed by using formula (8.19).

It should be noted that formulas (8.18) and (8.19) are used when the dusting with limestone dust is employed as the means of making the coal dust safe.

When, in order to prevent the danger of coal dust explosions the spraying of the dust with water is used or when the natural conditions of humidity suffice to make the examined coal dust safe, then — with the aid of the same nomogram shown in Fig. 8.24 — we get the answer whether the examined coal dust is able to propagate an explosion.

To this end it is necessary to compare the content of free water in the dust W_k, as found through the analysis of the dust, with the content of free water W_p read from the nomogram sufficient as a protection against the propagation of an explosion.

When $W_k < W_p$ then the dust is able to propagate an explosion and the content of free water in the dust ought to be increased at least to the value of W_p.

The quantity of water which should be added to every weight unit of the examined dust is found from the formula (8.20) given in Section 8.10.4 for the weight unit coefficient β. The manner in which the nomogram is used is best illustrated by the examples given hereunder. Natural-

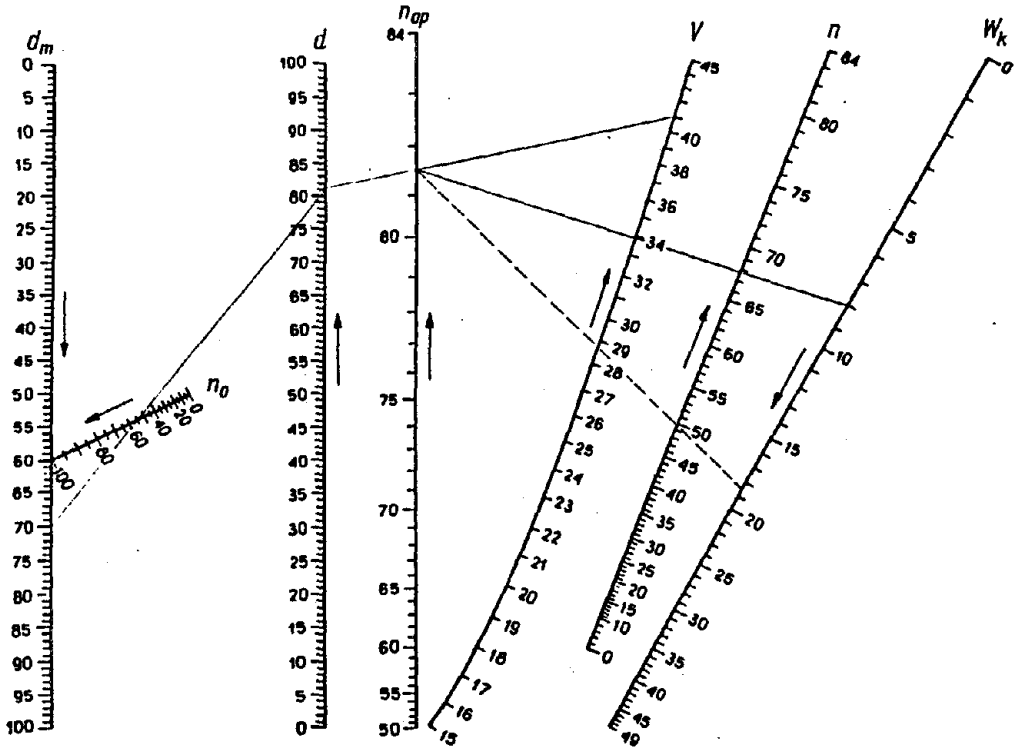


Fig. 8.24. The nomogram for finding the contents of incombustible solid matter and of free water in the dust of bituminous coal sufficient to make the given dust incapable of propagating an explosion worked out on the basis of formulas (8.13), (8.14), (8.16), (8.17); the conditions assumed: the strongest initiator 30mPII, the easiest dispersion conditions.

ly, the point of departure for making use of the nomograms is provided by data obtained through the physicochemical analysis of the samples of the dust and of the coal from the seam.

Example 1

Data: $V = 41\%$; $d_m = 70\%$; $n_0 = 54\%$; $n = 49.7\%$; $W_k = 8\%$ (n established from formula (8.16) by making use of the values of n_0 and W_k).

Solution I — when the content of free water, being variable, is left out of account.

In order to determine whether the given mine dust is able to propagate an explosion it is necessary to find with the aid of the nomogram the content of incombustible solid matter n_{0p} which makes the given dry dust safe as regards the propagation of an explosion, and then to compare the value of n_{0p} with the value of n_0.

To find the value of n_{0p} it is necessary to find — on the scaled line marked d_m — the point corresponding to the value of $d_m = 70$ percent and on the scaled line marked n_0 — the point corresponding to the value of $n_0 = 54$ percent.

By connecting these two points and prolonging the straight line until it crosses the scaled line marked d we get the number corresponding to the degree of the fineness of the pure coal dust contained in the examined mine dust. But there is no need of reading the value of d. The point on the scaled line marked d, reached by the prolonged straight line connecting our d_m and n_0 points, ought to be connected now by a straight line with the point on the scaled line V corresponding to the value of $V = 41$ percent.

The straight line so drawn crosses the scaled line marked n_{0p} at the point $n_{0p} = 81.5$ percent.

This value of n_{0p} represents the lowest content of incombustible solid matter in the dry mine dust which would make the dust safe as regards the propagation of an explosion.

As we see $n_{0p} > n_0$ since $81.5\% > 54\%$. It shows that the examined mine dust, when dry, is capable of propagating an explosion.

Using formula (8.18) we find $\alpha = 1.48$.

Solution II — with the content of free water $W_k = 8$ percent taken into account in view of the constancy of the humidity conditions in mine workings in this case, or when the constancy of the humidity conditions is assumed.

In order to find the content of incombustible solid matter n_p sufficient to make the dust safe, with $W_k = 8$ percent taken into account, the point $n_{0p} = 81.5$ percent on the scaled line n_{0p} ought to be connected by a straight line with the point $W_k = 8$ percent on the scaled line W_k. The point at which this connecting line crosses the scaled line n determines the value $n_p = 68$ percent. As $n = 49.7 < n_p = 68$ percent the examined mine dust with its content of free water is able to propagate an explosion.

When the dusting with limestone dust is to be employed in order to make the examined mine dust safe the weight unit coefficient α has to be found from formula (8.19)

$$\alpha = \frac{68 - 49.7}{100 - 81.5} \cong 1$$

Thus to every weight unit of the mine dust in question an equal weight unit of limestone dust ought to be added, for example, 1 kg of limestone dust to 1 kg of the mine dust. When the spraying with water is to be used to make the mine dust safe the weight unit coefficient β has to be found from formula (8.20)

$$\beta = \frac{68 - 49.7}{171 - 81.5} = 0.2$$

The correctness of the value of α, found as described above, can be verified by using the verification formula

$$n' = \frac{n + 100\alpha}{1+\alpha} = \frac{49.7 + 100}{2} \cong 74.8 \tag{8.35}$$

where n' denotes the content of incombustible solid matter in the humid dust with the limestone dust added in accordance with the weight unit coefficient α.

Naturally the value of n' refers to the new mixture of the dust containing water in the quantity designated by the symbol W_k' the magnitude of which is found from the formula

$$W_k' = \frac{W_k}{1+\alpha} = \frac{8}{2} = 4\% \tag{8.36}$$

The correctness of the findings is proved by the fact that the points: $n_{op} = 81.5\%$, $n' = 74.8\%$ and $W_k' = 4\%$ are placed on a single straight line connecting these points marked on the scaled lines n_{op}, n and W_k. The equation (8.13) is thus satisfied. This straight line does not appear in Fig. 8.24 as it would make the drawing less perspicuous.

In order to check the correctness of the value of β found in the above described manner the following verification formulas have to be used

$$n'' = \frac{n}{1+\beta} = \frac{49.7}{1.2} = 41.4\% \tag{8.37}$$

$$W_k'' = \frac{W_k + 100\beta}{1+\beta} = \frac{8+20}{1.2} = 23.3\% \tag{8.38}$$

where

n'' — the content of incombustible solid matter in the given dust with water added to it in accordance with the relevant weight unit coefficient β,

W_k'' — the content of free water in the ultimate mixture of the dust with water added to it in accordance with the relevant weight unit coefficient β.

The correctness of the findings is confirmed by the fact that the points: n_{op}, n'' and W_k'' are situated on a single straight line connecting these three points, marked on the scaled lines n_{op}, n and W_k, respectively.

Example 2

Data: $V = 31\%$; $d_m = 57\%$; $n_o = 40\%$; $W_k = 15\%$; $n = 34\%$

The dust in question has a high content of free water and, on account of this, the spraying of the dust with water is indicated in this case.

In order to find whether this dust is capable of propagating an explosion it is necessary to find the value of n_p and to compare it with the value of n; or to find the value of W_p and to compare it with the value of W_k.

The point of $d_m = 57$ percent on the scaled line d_m has to be connected with the point $n_0 = 40$ percent on the scaled line n_0. The point at which this straight connecting line crosses the scaled line d has to be connected then with the point $V = 31$ percent. When this straight line crosses the scaled line n_{0p} it determines the point $n_{0p} = 77$ percent. We connect this point with the point $n = 34$ percent on the scaled line n. Prolonging this straight line until it crosses the scaled line W_k we find the point $W_p = 25.2$ percent

$$W_p = 25.2\% > W_k = 15\%$$

which proves that the dust is capable of propagating an explosion. The answer to the question whether the dust is able to propagate an explosion can be obtained also by finding the value of n_p. To this end we connect the point $n_{0p} = 77$ percent with the point $W_k = 15$ percent on the scaled line W_k. The point at which this straight line crosses the scaled line n determines the value of $n_p = 51.3$ percent

$$n_p = 51.3\% > n = 34\%$$

The above inequality confirms the fact — previously established — that the dust in question is able to propagate an explosion.

The weight unit coefficient β, determining the least quantity of water which should be added to the dust to make it safe as regards the propagation of an explosion, has to be found from formula (8.29) the value of $q = 1.71$ being taken from Table 8.7. The coefficient in question amounts to

$$\beta \cong 0.2$$

In order to check the correctness of the value of β, found as described above, verification formulas (8.37) and (8.38) can be used. Having substituted the symbols in these formulas by the relevant values we get

$$n'' \cong 28.3\%; \quad W_k'' = 29.2\%$$

The points n_{0p}, n'' and W_k'' are situated on a single straight line in the nomogram shown in Fig. 8.24 which shows that the values sought for are correctly computed.

8.11.3. A nomogram for the initiator 50 cu m CH_4 (9.5%) and the easiest dispersion conditions

The nomogram presented in Fig. 8.25 is based on formulas (8.17), (8.25), (8.26) and (8.27) given in Section 8.10.6.

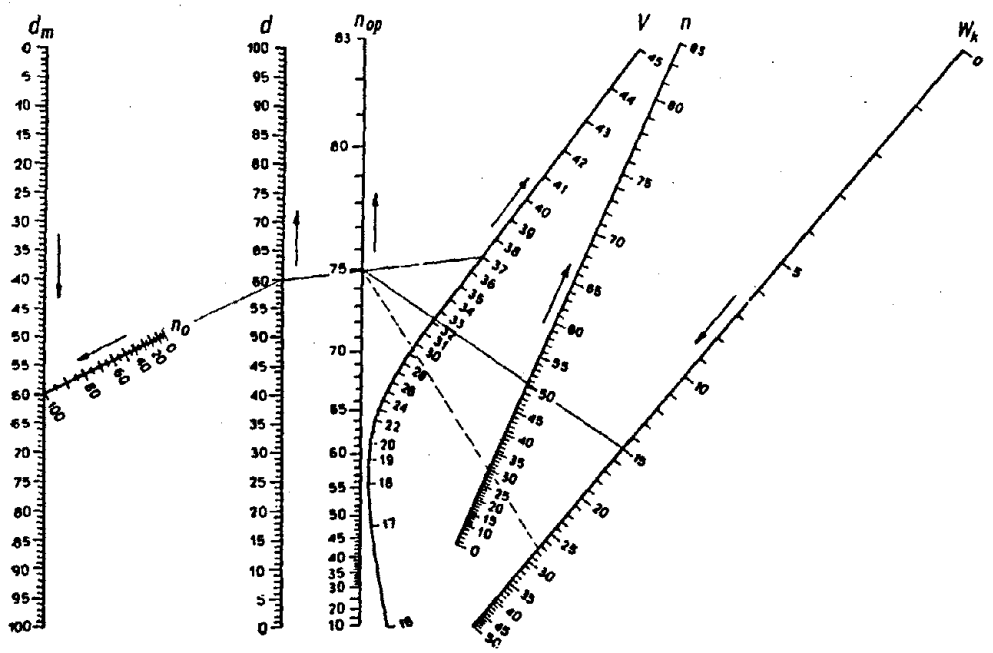


Fig. 8.25. The nomogram for finding the contents of incombustible solid matter and of free water in the dust of bituminous coal sufficient to make the given dust incapable of propagating an explosion worked out on the basis of formulas (8.25), (8.26), (8.27); the conditions assumed: initiator 50 cu m CH_4, the easiest dispersion conditions.

The way in which this nomogram can be used is analogous to that discussed in Section 8.11.2 with reference to the nomogram shown in Fig. 8.24.

Example 1

Data: $V = 37\%$; $d_m = 60\%$; $n_0 = 35\%$; $W_k = 15\%$; $n = 29.8\%$

The examined dust contains a considerable amount of free water $W_k = 15$ percent and, therefore, the use of the spraying with water is indicated as the means of making this dust safe.

In order to establish whether the dust in question is capable of propagating an explosion it is necessary to find the value of n_p.

The point of $d_m = 60$ percent is situated exactly at the crossing of the scaled lines d_m and n_0. Consequently there is no need of looking for the relevant point on the scaled line n_0. In this case the scaled line n_0 itself should be prolonged until it crosses the scaled line d. The point thus fixed on the scaled line d ought to be connected by a straight line with the point $V = 37$ percent on the scaled line V. The point at which this line crosses the scaled line n_{0p} determines the point $n_{0p} = 75$ percent. When this point

is connected by a straight line with the point $W_k = 15$ percent on the scaled line W_k we find the value $n_p = 50.5$ percent (on the scaled line n)

$$n_p = 50.5\% > n = 29.8\%$$

There is no doubt that the examined dust is able to propagate an explosion of course with the initiator 50 cu m CH_4 and in the easiest dispersion conditions such being the premises adopted as the basis for working out the nomogram presented in Fig. 8.25.

In order to determine whether a given dust is capable of propagating an explosion we can also find the value of W_p and compare it with the value of W_k. To this end we connect the point $n_{0p} = 75$ percent on the scaled line n_{0p} with the point $n = 29.8$ percent on the scaled line n; this straight line, prolonged until it crosses the scaled line W_k, indicates the value of $W_p = 27.5$ percent

$$W_p = 27.5\% > W_k = 15\%$$

The above inequality confirms that the examined dust is able to propagate an explosion — that is, that it does not contain enough free water.

The weight unit coefficient β has to be found from formula (8.20) with the value of $q = 1.63$ (from the Table 8.7); it amounts to

$$\beta \cong 0.24$$

In order to check the correctness of the value of β found as above described we use verification formulas (8.37) and (8.38) and get

$$n'' \cong 24.0\%; \quad W_k'' = 31.5\%$$

The points n_{0p}, n'' and W_k'' are situated on a single straight line as shown in the nomogram (Fig. 8.25) which confirms the correctness of the findings.

8.11.4. A nomogram for the initiator 30mPII and the most difficult dispersion conditions

The nomogram presented in Fig. 8.26 is based on formulas (8.17) and (8.28)–(8.31) discussed in Section 8.10.7.

The use of this nomogram is quite similar to the use of the nomograms shown in Figs. 8.24 and 8.25.

In the example given hereunder this nomogram was used to find both weight unit coefficients α and β.

Example 1

Data: $V = 41\%$; $d_m = 65\%$; $n_0 = 52\%$; $W_k = 12\%$; $n = 45.7\%$

In this case either the dusting with limestone dust or the spraying with water can be used in order to make the dust safe.

Solution I — when the dusting with limestone dust is to be employed and the free water content in the dust $W_k = 12$ percent is taken into account. In order to determine whether the examined dust is able to propagate an explosion one has to proceed in the manner described in preceding sections.

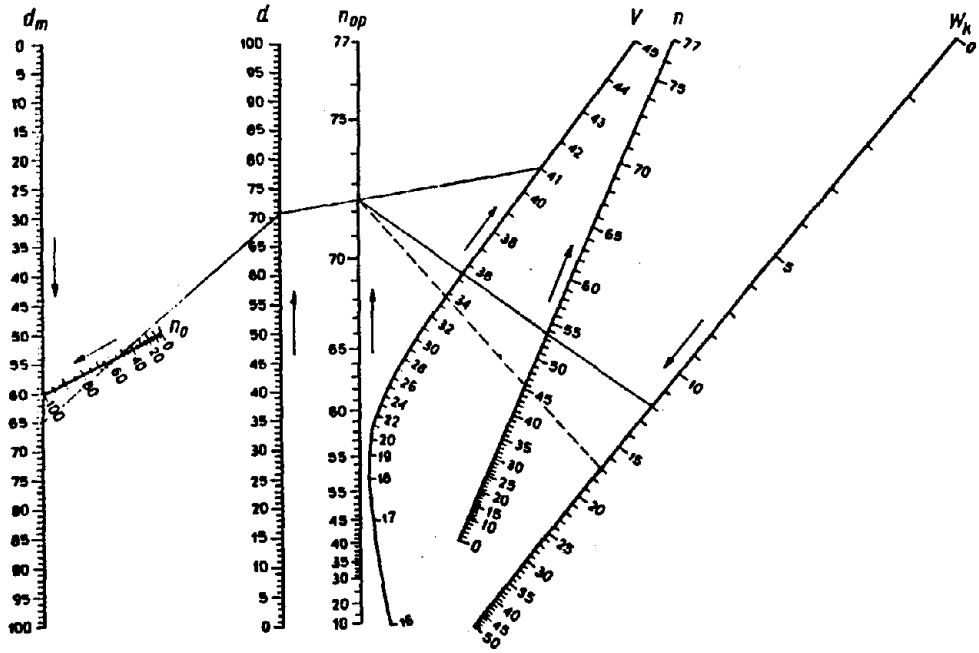


Fig. 8.26. The nomogram for finding the contents of incombustible solid matter and of free water in the dust of bituminous coal sufficient to make the given dust incapable of propagating an explosion worked out on the basis of formulas (8.28), (8.29), (8.30), (8.31); the conditions assumed: the strongest initiator 30mPII, the most difficult dispersion conditions.

The point $d_m = 65$ percent on the scaled line d_m has to be connected with the point $n_0 = 52$ percent on the scaled line n_0. The point at which this connecting line, prolonged, crosses the scaled line d has to be connected with the point $V = 41$ percent on the scaled line V. Where this straight line crosses the scaled line n_{0p} we find the point $n_{0p} = 72.5$ percent. By connecting this point n_{0p} with the point $W_k = 12$ percent on the scaled line W_k we find — at the point where this connecting line crosses the scaled line n — the point $n_p = 53.5$ percent

$$n_p = 53.5\% > n = 45.7\%$$

This inequality shows that the dust in question is able to propagate an explosion.

The same answer is obtained when finding the value of W_p. To this end the point $n_{0p} = 72.5$ percent has to be connected by a straight line with the point $n = 45.7$ percent on the scaled line n. The point at which this line crosses the scaled line W_k shows the value of $W_p = 17$ percent

$$W_p = 17\%; \quad W_k = 12\%$$

The above inequality confirms the fact that the dust in question is able to propagate an explosion.

It should be mentioned here that it is not really necessary to have the value of W_p established and compared with the value of W_k once it has been possible to compare the value of n_p with the value of n.

Form formula (8.19) we find the weight unit coefficient

$$\alpha \cong 0.3$$

In order to check the correctness of the value of α established as described above verification formulas (8.35) and (8.36) are used from which we get

$$n' \cong 58.3\%; \quad W'_k = 9.3\%$$

The points n_{0p}, n' and W_k are situated on a single line in the nomogram shown in Fig. 8.26 which confirms the correctness of the findings.

Solution II — when the spraying with water is to be used. Since in solution I it has been established that $W_p > W_k$ it remains to find the weight unit coefficient β from formula (8.20) with the value of $q = 1.56$ (taken from Table 8.7). We find

$$\beta \cong 0.1$$

Making use of the verification formulas (8.37) and (8.38) we get

$$n'' = 41.5\%; \quad W''_k = 20\%$$

The points n_{0p}, n'' and W''_k are situated on a single line in the nomogram shown in Fig. 8.26 confirming thereby the correctness of the findings.

8.11.5. A nomogram for the initiator 50 cu m CH_4 (9.5%) and the most difficult dispersion conditions

The nomogram presented in Fig. 8.27 is based on formulas (8.17) and (8.31)–(8.34) given in Section 8.10.8.

As an illustration of the way in which the nomogram in question can be used the solution of one example is given below.

Example 1

Data: $V = 34\%$, $d_m = 47\%$; $n_0 = 35\%$; $W_k = 10.5\%$; $n = 31\%$

Considering that the content of free water in the dust is relatively insignificant it is possible to assume that the workings will be dusted

with limestone dust in order to have them protected — that is, of course, if it is found that the dust present in the workings is capable of propagating an explosion.

The content of free water indicates also the possibility of having the workings sprayed with water. Naturally prior to taking such a decision it is necessary to find whether the coal dust in question will absorb well the sprayed water.

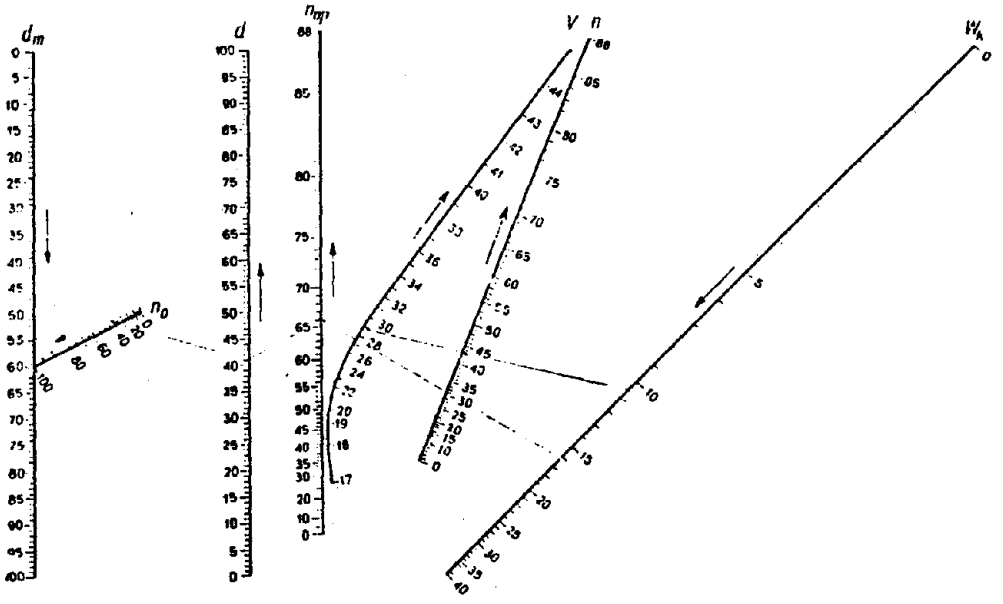


Fig. 8.27. The nomogram for finding the contents of incombustible solid matter and of free water in the dust of bituminous coal sufficient to make the given dust incapable of propagating an explosion worked out on the basis of formulas (8.31), (8.32), (8.33), (8.34); the conditions assumed: initiator 50 cu m CH_4, the most difficult dispersion conditions.

First of all it should be found — on the basis of the established characteristics of the dust — whether it is able to propagate an explosion.

It is assumed that humidity conditions in the examined workings are constant so that, leaving out of account the event of the presence of dry coal dust, the free water content in the dust should be taken into consideration. The procedure to be followed in order to get the answer concerning the ability of the dust to propagate an explosion is quite analogous to that described in previous examples.

The point $d_m = 47$ percent and the point $n_0 = 35$ percent determine the straight line which, in its turn, determines a point on the scaled line d. This last point and the point $V = 34$ percent jointly determine the straight

line which, at the point of crossing the scaled line n_{op}, indicates the value of $n_{op} = 66$ percent. This point again, jointly with the point $W_k = 10.5$ percent, determines the value of $n_p = 43$ percent.

$$n_p = 43\% > n = 31\%$$

Obviously the dust in question can propagate an explosion. The answer to our question is univocal. It is possible to obtain the same answer also by finding the value of W_p.

The points $n_{op} = 66$ percent and $n = 31$ percent determine the straight line which, in its turn, determines the point $W_p = 16.2$ percent.

$$W_p = 16.2\% > W_k = 10.5\%$$

Solution I — when the dusting with stone dust is introduced.

The weight unit coefficient α according to fomula (8.19) amounts to

$$\alpha \cong 0.4$$

In order to check the correctness of the findings we turn to the verification formulas (8.35) and (8.36) and get

$$n' = 50.7\%; \quad W_k' = 7.5\%$$

The points n_{op}, n' and W_k' are situated on a single line in the nomogram presented in Fig. 8.27 which constitutes a proper confirmation of the correctness of the findings.

Solution II — when the spraying with water is used.

The weight unit coefficient β computed in accordance with $q = 2.16$ (taken from Table 8.7) amounts to

$$\beta \cong 0.1$$

Using verification formulas (8.37), (8.38) we find

$$n'' = 28.2\%; \quad W_k'' = 18.6\%$$

The points n_{op}, n'' and W_k'' are situated on a single straight line in the nomogram shown in Fig. 8.27 which constitutes a proper confirmation of the correctness of the findings.

8.11.6. Closing remarks about the way of using the nomograms

From the numerous examples given here of how the nomograms are used it can seen that it is exceedingly easy to use them. It can be established in a very simple way whether a given mine dust is able to propagate an explosion and, then, by making use of very simple formulas the minimum quantities of limestone dust or of water can be computed, which ought to be added to the given coal dust in order to make it safe as regards the propagation of an explosion. Naturally, the last mentioned step

has to be taken only if the nomogram shows that there is a danger of the propagation of a coal dust explosion.

It is advisable always to check the correctness of findings by using the verification formulas that are also exceptionally simple.

It should be stressed again that the getting of correct results from the employment of nomograms depends primarily on the professionally proper and fair way of collecting the samples of mine dust from the examined workings and on the correct performance of the physical and chemical analysis of these samples.

If for any reason the content of volatile matter in coal is temporarily unknown $V = 40$ percent can be taken for the Upper Silesian coal: ultimately, this would give results with a good safety margin.

It is necessary to remember that weight unit coefficients for limestone dust or water indicate the minimum quantities that should be added to a given mine dust. In practice the supplementary quantities of limestone dust or water ought to be much larger since it is important that the limestone dust or water as a supplement be distributed equally in the entire cross section of the workings. By how much the weight unit coefficient in question ought to be increased depends on the way in which the operations of dusting with stone dust or spraying with water are executed; a great deal depends here on the careful performance of these operations. Consequently, no single factor can be recommended by which the coefficient in question should be increased.

The correctness of the supplementary dusting with limestone dust or spraying with water can be checked with the utmost reliability by performing control analyses. To the person who reads this chapter on the nomograms a question might suggest itself, quite analogous to that which might come to the mind of those who read the chapter on general formulas, which of the nomograms ought to be used in a given case? Though this problem has already been dealt with yet considering its fundamental importance the explanations which follow ought to be repeated.

The doctrine of this book as a whole is that the explosibility of coal dust depends upon a number of parameters.

In mines the number of factors which play some part in the problem of coal dust explosions is actually greater than the number of the factors which were put in order and analyzed and are discussed in this book.

Actually coal dust explosions can occur in conditions varying greatly as to the physicochemical properties of the dusts, the distribution of the dust in a working, the conditions predominant in workings, the wide range of initiators, the presence and distribution of firedamp in workings, etc.

The simultaneous appearance of such a large number of diverse conditions, creating a certain system of a random character at a given place

and time, cannot be conjectured beforehand especially on a scale of a huge coal industry, such as, for example, that existing in Poland.

It would have been wrong to try and make a forecast of mean random conditions of this kind. The mining experience of many years, as well as a general analysis of contingencies, show that the occurrence of particularly adverse coincidences is always possible. Statistical analysis fully supports this view. As far as the explosibility of coal dust is concerned, when the matter is considered on the scale of a huge coal mining industry, the probability is high of the concurrence of the most adverse factors that one is likely to encounter in practice and which are conducive to the development of a coal dust explosion.

The general formulas, as well as the nomograms discussed here, have been worked out with reference to strong explosion initiators, to the optimum concentration of mine dust, to the easiest and the most difficult dispersion conditions in addition to taking account of the established physicochemical properties of coal.

There should be no doubt about the fact that, in making use of the formulas or the nomograms, it is most advisable to assume the initiator to be practically the strongest (30mPII) and the dispersion conditions the easiest.

It ought to be stressed that both the formulas and the nomograms have been worked out taking account of the diversity of the fineness of coal dust and of the free water content being below that which directly prevents the dust from propagating an explosion. As a rule binding regulations in different countries disregard the variability of these parameters assuming that mine dust can generally be of a very high degree of fineness, and dry — that is, devoid of free water.

These parameters were included in the reckoning very strictly when the general formulas and nomograms have been worked out. Compared with the requirements set forth in the general regulations governing the prevention of the danger of coal dust explosions the use of the formulas and the nomograms discussed here presents a tremendous advantage.

A fundamental question arises in connection with what was said above, namely, whether — and in what measure — the general formulas and the nomograms may be used in the mining practice without perceptibly lowering the degree of the safety in mines as far as the possibility of a coal dust explosion is concerned.

The general formulas presented in Section 8.10, though relatively simple, require toilsome calculations. The nomograms practically eliminate the toilsomeness of the calculations and, consequently, encourage the use of the formulas. The simplicity of the use of the nomograms ought to be

conducive to the growth of the tendency to taking willingly the advantage offered by their use.

In accordance with what has already been said the question of the use of the nomograms or formulas should be approached with great discretion and prudence. In the first place they ought to be used for one's own evaluation of the hazard of coal dust explosions to which mines are exposed irrespective of the regulation requirements.

The essential point of the matter is whether the result obtained in this way may be regarded as conclusive when it shows that a given dust is unable to propagate an explosion, though it had not been made safe through stone dusting, etc. in accordance with the regulation requirements. Cases of this kind may be quite frequent since the regulations disregard many a parameter taken account of in the formulas. The regulations, as a matter of fact, set forth generally the required content of incombustible solid matter without going into the question of the fineness of the dust leaving out the question of the content of free water and treating the mine dust as dry; naturally the above refers to cases in which stone dusting is prescribed for the given workings. When the spraying with water is the method prescribed for making mine dust safe the regulations in force, up to the present time, leave out of account the content of incombustible solid matter in the dust.

Ultimately, as it clearly follows from the idea underlying the formulas, regulation requirements give a considerably wider margin of safety than the formulas.

If the steps to make coal dust safe were based on the formulas instead of the fulfilment of the very simplified general regulation requirements it would have resulted in a very far going change of the requirements as compared with those set forth in the regulations in force up to the present time.

It must be underlined that, so far, in no country the safeness of coal dust is being secured by measures based on the formulas or nomograms presented in this book. As was mentioned already, apart from the initial attempts of Taffanel, Audibert and the author of this book at an early period between the wars, no such formulas had ever been worked out.

It is necessary to state in the summing up that, so far, the binding regulations in all countries are general in their character and make the requirements concerning the content of incombustible solid matter in the dust dependent exclusively upon the content of volatile matter in the coal.

If it were decided to base the requirements, concerning the safeness, of coal dust as regads the propagation of an explosion, on the formulas or nomograms discussed here it would have been necessary to have a guarantee that the collection of the mine dust samples will be done fairly and

correctly and that the formulas will be correctly used. To make this actually possible it is necessary for the supervising personnel in mines to have a sufficient knowledge of problems connected with coal dust explosions. The level of this knowledge would have to be verified in a strictly specified manner by mining authorities. Likewise mine laboratories entrusted with the duty of analyzing mine dust would have to represent a level approved by mining authorities.

The whole problem of the hazard of coal dust explosions shows that the task of collecting representative samples of mine dust is in itself a hard task calling for a good knowledge of the problem and for a great scrupulosity.

In view of the great importance of the correct prevention of the hazard of coal dust explosions mining authorities would have to undertake, in accordance with a tradition of long standing, a more intensive control of the mine which would be permitted to base, on the use of the formulas or of the nomograms, the steps they take to make their coal dust safe as regards the propagation of an explosion.

8.12. The Accuracy of Determining the Fineness d of Pure Coal Dust

The fineness d of pure coal dust in the mine dust cannot be determined experimentally; it can only be computed on the basis of the fineness of the mine dust d_m and of the content of incombustible solid matter in the mine dust n_0.

The formula (8.17) given in Section 8.10 for computing the content of the dust fraction < 75 μm in pure coal dust

$$d = \frac{100(d_m - 0.6n_0)}{100 - n_0}$$

is an approximate formula.

The precise formula for finding the value of d has the form

$$d = \frac{100(d_m - 0.6k)}{100 - k} \tag{8.39}$$

where k represents the content of limestone dust in the mixture with coal dust.

In the formula (8.17) the content k has been replaced by the content of incombustible solid matter n_0 as the value of n_0 is easily and directly found through the chemical analysis of the dust.

The content of limestone dust k, on the contrary, is not known in a direct way.

Though it can be found through an analysis, yet to this end, the scope of the analysis would have to be considerably expanded.

The content k can also be computed but this necessitates the previous finding by laboratory methods of the content of ash p in pure coal dust which it is not easy to do. The quantity of the fraction k can be found then from the formula

$$k = \frac{100(n_0 - p)}{100 - p} \tag{8.40}$$

The precise value of d, therefore, is determined by using formula (8.39) having previously computed the value of k from formula (8.40).

The approximate formula (8.17) requires neither the finding of the ash content p, nor the computing of the value of k and therefore it is more simple to use.

The magnitude of the error, resulting from the use of formula (8.17), may be found by substituting the right side of equation (8.40) for k in formula (8.39)

$$d = \frac{100(d_m - 0.6n_0)}{100 - n_0} + \frac{(60 - d_m)p}{100 - n_0} \tag{8.41}$$

The difference r between the formulas (8.39) and (8.17) amounts, therefore, to

$$r = \frac{(60 - d_m)p}{100 - n_0} \tag{8.42}$$

The difference expressed by formula (8.42) represents exactly the error which is committed when using the approximate formula (8.17) instead of the precise formula (8.39).

The difference in question grows as the value of d_m diminishes. The lowest value of d_m amounts to $0.6k$. For this value of d_m the value of $d = 0$.

Substituting d_m by $0.6k$ in formula (8.42) and making use of formula (8.40) we get

$$r_{max} = \frac{60p}{100 - p} \approx 0.6p \tag{8.43}$$

The highest value of the error obtains for $d = 0$.

As the computed value of d grows the value of the error diminishes.

The value of the error as depending on the computed value of d is found from equations (8.41) and (8.42) after the elimination of the variable n_0

$$r = \frac{(60 - d)p}{100 - p} \cong \frac{(60 - d)p}{100} \tag{8.44}$$

Equation (8.44) clearly shows that the error considered here diminishes as the value of d grows. For $d = 60$ this error amounts to 0 and for $d > 60$ it gets the minus sign. This means that by using the approximate formula (8.17) a larger value is obtained than by using formula (8.39).

On the other hand for $d < 60$ somewhat diminished values when using formula (8.17) are obtained.

For the coal from Upper Silesian mines the value of p oscillates within the interval $1 \leqslant p \leqslant 15$ percent.

The maximum error in the computation of the value of d from the approximate formula (8.17) obtains in the case of $d = 0$ and amounts to

$$r_{max} = 0.6 \cdot 15 = 9$$

It means that, when from formula (8.17) we get for $p = 15$ percent the value of $d = 0$, then the precise value should amount to $d = 9$ percent. This will cause an error in the computed value of n_{0p}. The error in the computation of the value of n_{0p} in this case does not exceed 5 percent.

Similarly from equation (8.44) it is found that for $d = 20$ percent and $p = 15$ percent the precise value of $d = 26$ percent and for $d = 40$ percent and $p = 15$ percent the precise value of $d = 43$ percent.

As can be seen from the above only low values of d, computed from formula (8.17), have a relatively inconsiderable influence on the value of n_{0p}. In such cases it could be recommended to correct the error in the following way: when the computed value of d amounts to less than 40 percent to the value so found 5 percent should be added. In practice this procedure would be found much simpler than the finding of the value of p and the computation of the value of k from formula (8.40) which, in the course of the computation, ought to be substituted for n_0 in formula (8.17) or in the nomogram.

For values of $d > 40$ percent obtained by using formula (8.17) no amendments are required.

It may happen in practice that, in spite of using the precise formula (8.39) or a nomogram, a minus value of d is obtained. If the value of d approximately equals 0 (such cases are possible) it is the consequence of errors with which are burdened the found values of d_m, n_0, p and k in the dust. In such cases the value of d should be assumed to be $d = 0$ and for this value the value of n_{0p} ought to be found. The same suggestions will apply in the cases in which the values of d — computed or found from a nomogram — are above 100 percent.

The explanations given above are valid when we deal with a mine dust composed of pure coal dust from the seam plus limestone dust used for dusting the workings.

In practice most frequently the dust contains, in addition to the men-

tioned components, some stone dust from the crushed rock of the roof and floor of the working. Naturally this creates additional complications. In order to determine the natural content of incombustible solid matter in the dust, called the ash, it would be necessary to stop the dusting of the working with limestone dust for a time and then, in the mine dust appearing under such conditions, to find the content of ash.

The dust from the crushed rock of the roof and floor can affect the findings only if there is much of it and its fineness differs considerably from that of the limestone dust which is assumed to be 60 percent.

The fact that the content of incombustible solid matter in the mine dust, originating from the crushed rocks of the roof and floor, is left out from the considerations presented here contributes only to the securing of a larger margin of safety for the results obtained by using the formulas or nomograms.

9. STOPPING THE DEVELOPED COAL DUST EXPLOSIONS

9.1. STONE DUST BARRIERS FOR STOPPING COAL DUST EXPLOSIONS

9.1.1. General information

Any of the means of preventing the hazard of coal dust explosions, discussed in a sequence representing the particular lines of defense against explosion disasters, might, unfortunately, fail now and again under the operational conditions in mines. The causes to which the nonfulfilment of the respective tasks of the different lines of defense can be ascribed were discussed in the special chapters devoted to the consideration of the defense lines in question. In cases of such failures the initiated coal dust explosions will develop.

The range of a coal dust explosion fluctuates between wide limits depending on various parameters; upon the extent of this range depends the dimension of the possible disaster. There is no doubt, therefore, that in a case of a developing coal dust explosion it is most desirable to ensure that its course be made as short as possible.

Stone dust barriers and water barriers are used to limit the range of a coal dust explosion — that is, to stop an already developed explosion. The barriers in question were discussed in separate chapters.

The conception of stone dust barriers comes from the frequently cited here French investigator J. Taffanel [167]. The principle underlying the Taffanel's idea was very simple based on the fact that the flame of a coal dust explosion is preceded by a blast. If on the route of an explosion especially constructed shelves were placed carrying stone dust, the blast would cause the dispersion of stone dust throughout the cross section of the working. Provided that the cloud of stone dust thus formed is of an adequate concentration and occupies a sufficiently long section of the working the explosion flame, having reached the incombustible medium in the form of the above mentioned cloud, cannot develop further and becomes extinguished. In this way the development of an explosion is stopped and, consequently, its range is restricted. Unquestionably this idea

of Taffanel had been quite good but it required a very thorough elaboration. It has been explained in more detail in preceding chapters that the ways in which coal dust explosions develop vary quite considerably and that, therefore, the effectiveness of barriers depends on many fundamental factors. Taffanel had no adequate possibilities for investigating the problem of barriers, a problem — by the way — requiring that a lot of experiments be carried out under diverse conditions. As a result, barriers of the Taffanel type installed in the *Clarence* mine failed to stop an explosion [131].

9.1.2. The importance of the barriers

In view of the very great length of the workings which ought to be protected against the propagation of coal dust explosions, as has been explained in Sections 8.6 and 8.7, it is hardly probable that the regulation requirements concerning the suppression of the danger of coal dust explosions will be faultlessly complied with in all such workings. Besides, the regulations in which these requirements are set forth (Table 8.5) are in many cases inadequate. In the circumstances it is necessary to consider seriously the possibility of both an initiation and a development of coal dust explosions. Thus, it becomes an absolute and unquestionable necessity to have at one's disposal some means to be used as the last defense line, of the highest possible dependability for checking the range of an explosion. Barriers are the means of this type. The importance of this problem had been fully realized particularly in the *EM Barbara* where a very large number of investigations was carried out on this problem; the number of experiments carried through exceeds 1700 and the results of these investigations were published in thirteen scientific bulletins jointly covering 450 pages of print [22], [26], [36], [42], [43], [53], [54], [56], [58], [59], [65].

9.1.3. Requirements with regard to barriers

Requirements laid down with regard to barriers, expressed in the most general terms, are as follows:

— they ought to be able to stop unfailingly all kinds of coal dust explosions that could possibly occur in mines;

— they should be able to stop coal dust explosions in workings of the diverse cross section areas one meets with in mines;

— their construction ought to be as simple as possible in order to reduce to the minimum the possibility of errors in their erection and to facilitate the control of their condition;

— being brought into action accidentally, in the course of mining operations, they should not cause any harm to the workers;

— they should stop the development of a coal dust explosion at as small a distance as possible from the face of the workings (generally from the place of the initiation of an explosion); in any case the minimum distance at which the barrier would act effectively should not exceed 60 m;

— they should not be excessively resistant to the air current;

— their sensibility to the factors which can make them act has to be balanced so as to represent a compromise between their ability to be brought into action by a weak blast of an explosion and, on the other hand, their inability of being easily overturned in the course of the ordinary mining operations;

— they should not unload excessive quantities of stone dust or of water at one place as this would not produce any effect particularly when the explosions are rather weak since in such cases the bulk of the stone dust or of water falls to the floor of the working and is not dispersed by the weak blast in consequence playing no role in the explosion; in other words, the separate units of a barrier should not carry an overload of either stone dust or water;

— their construction ought to make the erection of barriers in their proper places easy under conditions prevailing in mines; particularly the construction of barriers should take account of the fact that a part of the cross section of a working is occupied by ventilation pipes, ducts, etc.; the erected barriers must not be sheltered from the action of the blast by roof bars, etc., or by being erected in a place where the roof has been ripped;

— the barriers should not impede the traffic of workers which means that the going underneath the barriers should not present any difficulties; the passage for men has to be provided either under the barrier, or on a side of the barrier; otherwise the barrier units will be frequently overturned during the normal operations with the effect that, ultimately, the quantity of stone dust or of water on a barrier will become insufficient.

The fulfilment of all of the above requirements is not easy. The examination of the effectiveness of the barriers, considering the wide range of different types of coal dust explosions, necessitates the carrying out of very many experiments on a large scale. This question is of great importance but often it is not sufficiently appreciated. Scientific research institutions, interested in the problem of the suppression of coal dust explosions, frequently get newly invented types of barriers submitted to them and the inventors expect such institutions to pronounce almost immediately an opinion on the effectiveness of these barriers. The misunder-

standing consists in this that such inventors, mostly possessing little knowledge of the problems of explosions in mines, do not realize that in such cases it is necessary to carry out extensive investigations which take a long time and are very expensive. As a very convincing example reference can be made to the large number of investigations, which were carried out in the *EM Barbara* since long ago, on the type of the barrier that had actually been in use in Polish as well as in foreign mines. Particularly valuable are such types of barriers which, beside having been proved in very extensive tests, did confirm their merits in the actual use in mines and passed through something like a baptism of fire by stopping explosions under diverse conditions in mines. Naturally in order to be able to use particular barriers in a mine it is necessary that this particular type should be approved for use by the mining authorities.

9.1.4. The basic types of stone dust barriers with which the largest number of tests was made

9.1.4.1. General information. Different types of barriers are in use in different countries. They always consist of many units generally referred to as shelves or containers depending on the type of the barrier. The term barrier is always meant to denote the entire set of shelves or containers. But when one speaks about a barrier of a given type one always has in mind a barrier unit — that is, a shelf or a container. Barrier units may be of diverse styles of construction.

It has been decided to give here the description of only such types of barriers whose effectiveness had been properly investigated and which are therefore widely used. Some of the types of barriers that are used abroad either had not been examined at all, or the extent of the examination had been very limited.

It is not necessary to describe all such barriers here. We have restricted ourselves in this book to the description of the barriers of the *EM Barbara* type, of the *Versuchsgrube* type and of the American barriers. Actually American barriers are not being used but they are worthy of a description as they were examined both in USA and in Poland.

9.1.4.2. Barriers of the *EM Barbara* type. The *EM Barbara* type barrier is shown in Fig. 9.1. This barrier had been designed in the outcome of many basic investigations, and the verification of its effectiveness has been done under very diversified conditions described in publications: [22], [26], [36], [42], [43], [53], [54], [59], [60].

The *EM Barbara* type barrier is composed of the following elements (Fig. 9.1): the props attached to the support; the brackets placed on the props; the frame often referred to as the ladder; and the platform (the

shelf) of loose wooden dust boards. These boards are either 35 or 50 cm long and, therefore, the shelves are either narrow — 35 cm, or broad — 50 cm. All these elements are made of timber and only the props are attached. The other elements are placed loosely.

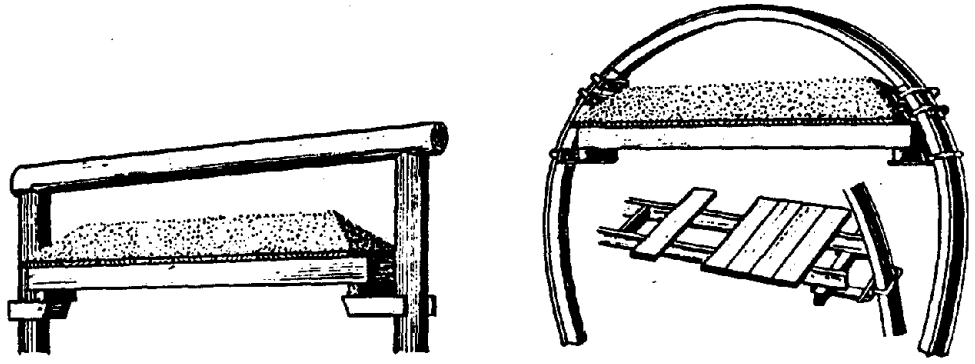


Fig. 9.1. Barrier of the *EM Barbara* type.

There is a possibility of using plastics instead of timber.

A very important role in the structure of the barrier is played by the depth of the frame. The boards of which the frame is made, placed vertically and connected with each other at two or three points, very effectively facilitate the displacement of the shelves by the explosion blast. To this end the depth of the frame — that is, the breadth of the boards of which it is made ought to be sufficiently large. It should amount to from 20 to 30 cm. For the larger is the surface of the boards of which the frame is made, the higher is the force with which the blast that precedes the flame acts on it; the wider shelves (50 cm) in particular have a frame of greater depth on account of the heavier load of stone dust placed on them.

The simplicity of the construction of the above described barrier of the *EM Barbara* type is its particular virtue. Very expedient is the construction of the platform from loose, well fitting thin boards. Stone dust placed on the platform subsides with the passage of time. The loose wooden dust boards of which the platform is made, when the barrier is put into action, help to break the mass of the dust and thus aid in its dispersion. Besides, it is most advisable to use waterproof stone dust for the barriers since not only it remains dispersible under humid conditions for a much longer time than ordinary dust, but also it is much less cohesive and, consequently, it can be more easily dispersed.

As a rule the barrier is put into action in a simple way. There are differences, however, depending on the violence of the explosion.

When the blast is strong the frame is lifted together with the platform.

In the course of this movement stone dust is raised together with the loose boards and becomes dispersed by the blast throughout the entire cross section of the working. When the explosions are of a weaker type the blast at first lifts up and overturns the loose boards. Stone dust which falls off these boards is then raised up by the blast and dispersed.

Obviously for a proper action of the barrier it is necessary that stone dust be raised up by the blast. In the case of a very weak blast and a rather heavy load of stone dust placed on the platform, it may happen that the energy of the blast is too low for raising up the whole dust so that the larger part of it falls down to the floor. This phenomenon occurs also when the explosions are so weak as to be scarcely able to push the frame off the brackets on which it rests.

It follows from the description of the way in which barriers are put into action that, in cases of weak explosions, the most advantageous are the smallest possible loads of stone dust on the platforms. This effect is achieved by using shelves 35 cm broad. These shelves are equally effective in cases of violent explosions. It is only necessary that the distance between the shelves should not be too long. The shelves 50 cm broad, on the contrary, might be less effective in cases of weak explosions. The reason is simple enough: such shelves are not quite so easily put into action. In view of the difficulty of foreseeing the character of the threatening explosion it is generally more expedient to use 35 cm shelves. In practice, unfortunately, 50 cm shelves are used more frequently since such shelves permit of depositing the quantity of stone dust required by regulations on a smaller number of shelves, and the entire barrier can then occupy a smaller section of the working.

On account of the great importance of the movements of the separate elements of a barrier motion pictures were taken of the putting of barriers into action by using the *Pentazet* 35 mm film camera with the taking frequency 350/sec. The barrier was placed in front of a surface experimental gallery in which explosions were initiated. On the average, in the course of each experiment, about 500 shots were obtained illustrating the way in which barriers are put into action.

In the course of these investigations the separate movements of the shelf elements were being determined: the arrival of the front of the blast to the barrier, the loose boards of the platform beginning to move, the frame and the consecutive layers of the limestone dust being moved, the putting into action of the whole barrier. During every test the time was measured in which the shelf has been completely put into action.

In such circumstances it was possible to separate the movements of the particular elements of the barrier and to fix the time in which the shelf was set completely to the performance of its task [59].

When the blast reaches the barrier it causes at first the raising up of only the surface layer of stone dust. Investigations carried out on the raising up of the layers of stone dust 1, 2 and 3 cm below the top of the heap have shown that these layers begin to move as a rule about 100 milliseconds after the loose wooden dust boards have started to move. Naturally these intervals of time depend on the force of the blast.

The description of the movements of the shelf elements discussed here refers to relatively weak explosions.

The pertinent investigations supplied clear evidence of the fact the dispersion of the bulk of stone dust is the effect of the putting into action of particular elements of the barrier, in the first place, of the loose boards which make the platform of the shelf. This is an important statement because it concerns the substance of what is meant by the putting into action of the shelf elements.

It has been found in the course of these investigations that the frame is moved, in the majority of cases, about 30 milliseconds before the loose boards of the platform begin to be raised.

The course of the putting into action of the shelf elements depends on the breadth of the shelf and on the depth of the frame.

Figure 9.2 illustrates the way in which a shelf of the *EM Barbara* type, 200×50×10 cm, is put into action; 10 cm denotes the depth of the frame. In this figure it can be seen that the loose boards, heretofore closely fitting each other, are being overturned almost to a vertical position in which they come apart and, thus, naturally, disperse the limestone dust. While this goes on, the frame is thrown off the props.

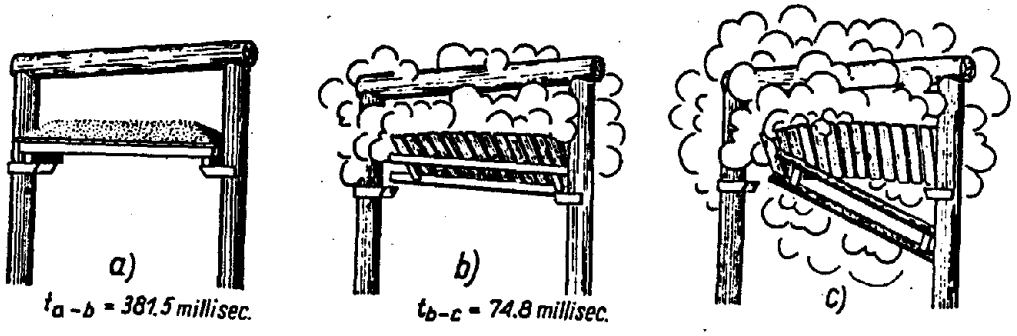


Fig. 9.2. The way in which a stone dust (102 kg) barrier of the *EM Barbara* type, 200 × 50 × 10 cm, is put into action.

Figure 9.2 shows also the time intervals between the consecutive positions occupied by the shelf elements. Figures 9.2*a*, *b*, *c* are drawn according to the motion pictures taken of the tests.

The process of putting into action the elements of the shelf 200×
×35×20 cm, shown in Fig. 9.3, is different. The frame, in this case of a greater depth and bearing a lighter load od stone dust, is thrown out by the explosion blast from under the loose boards which are lifted up to almost a vertical position and come apart causing the stone dust to be dispersed.

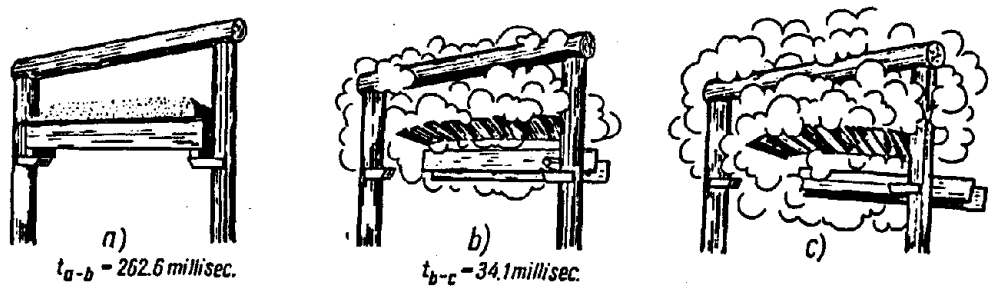


Fig. 9.3. The way in which a stone dust (62 kg) barrier of the *EM Barbara* type, 200 × 35 × 20 cm, is put into action.

Table 9.1

Results of Measurements of the Total Time t_c of Putting into Action Stone (Limestone) Dust Barriers and Water Barriers in Conditions of Weak Methane Explosions (Shelves 200 cm Long)

Shelf of container type	Breadth of shelves cm	Depth of the frame cm	Limestone dust or water load kg	Number of experiments	Mean total time of putting shelves/containers into action, t_c, millisec
		Stone (limestone) dust barriers			
EM Barbara	35	20	62	13	487
EM Barbara	50	10	102	11	595
EM Barbara	50	20	102	25	519
Dortmund	60	—	160	9	541
		Water barriers			
EM Barbara polystyrene containers	60×33×28		37.5	19	186

The motion pictures taken of the test make it possible to examine very accurately the process of putting the shelves into action and of dispersing stone dust. The tests described permitted to measure the time t_c necessary for completely putting the shelves into action. The results are

listed in Table 9.1. The same table contains the values of t_c for the *EM Versuchsgrube* barriers, called in short *Dortmund*, and for the polystyrene water containers of which water barriers are composed.

Dynamic pressure sufficient to put a barrier into action through weak explosions, is a magnitude of fundamental importance as it characterizes the case with which a barrier can be made to operate [58]. Appropriate experiments were carried out in a surface experimental gallery and just outside this gallery. Conditions for putting barriers into action were more favorable inside the gallery than outside of it. These experiments were carried through with barriers of the *EM Barbara* type 200×50×20 cm. The results of the experiments are given in Table 9.2.

Table 9.2

Scheduled Results of Investigations on the Minimum Dynamic Pressures which Will Put into Action Stone Dust—(s.d.) and Water (H_2O) Barriers

Type of barrier	Dimensions of barrier cm	Quantity of stone dust or water on the barrier kg	Dynamic pressure (kN/sq m) under conditions		Number of experiments
			very favorable	less favorable	
Barbara s.d.	200×50×20	100	0.8–1.3	0.8–3.0	20
Barbara s.d.	200×35×10	60	0.6–0.8	1.8–3.0	11
	200×35×20	60	0.6–0.8	0.8–2.2	8
Dortmund s.d.	190×60	160	2.1–11.0	3.0–11.0	17
Barbara H_2O — fixed rigidly	60×33×28	37.5	3.0–6.0	7.0–15.0	30
Barbara H_2O — placed loosely	60×33×28	37.5	0.9–10.0	1.4–13.2	46

9.1.4.3. Barriers of the *Dortmund* type. In West Germany, since quite a long time, barriers are in use composed of shelves shown in Fig. 9.4. The essential difference between these barriers and the *EM Barbara* type barriers consists in this that *Dortmund* barrier represents a platform of longitudinally placed boards resting on boards put accross a pair of rails. The rails in question can be attached to the support or placed on special props. Besides, and this is very important, the *Dortmund* barrier has no element which could help to put the shelves into action when explosions are of a weaker nature. In the *EM Barbara* type barriers there are such elements in the form of the frames 20 to 30 cm deep placed as shown in Fig. 9.1. Investigations on the *Dortmund* type barriers were carried out on

a large scale in the *EM Tremonia* in the Federal Republic of Germany [78], [102], [121], [152], [153], [154].

The *Dortmund* type barriers are of good effect with strong coal dust explosions similarly to other barriers of the shelf type provided that the blast of the explosion is strong enough to overthrow the shelf and to disperse the dust. On the other hand with weak, or particularly weak, explosions these barriers are likely to fail as they will not be put into action.

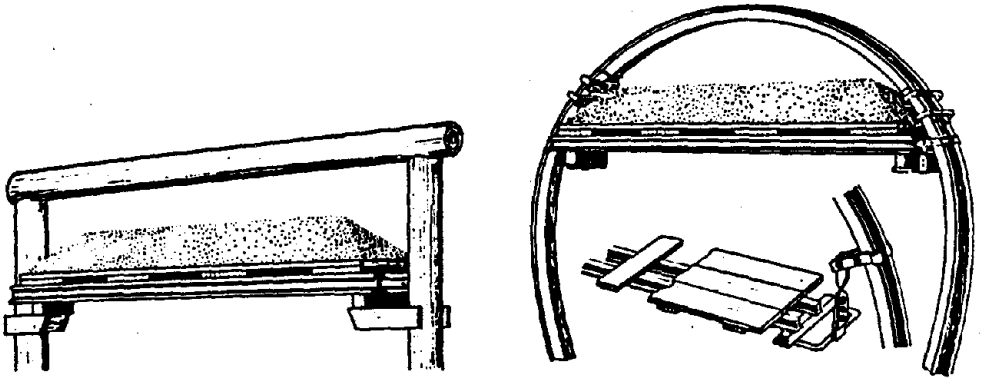


Fig. 9.4. The *Dortmund* type barrier.

How much stronger the dynamic pressure must be in order to put into action the *Dortmund* barriers than the pressure necessary to do the same to the *EM Barbara* type barriers can be seen in Table 9.2 for the favorable, as well as for the less favorable, conditions under which experiments had been made.

The two values of the dynamic pressure, given in the pressure column of the Table 9.2, have the following meaning: the smaller number expresses the pressure at which the barrier could not be put into action under any conditions; the larger number indicates the pressure at which — and over which — the barrier had been put into action every time. The interval between these numbers represents the value of the dynamic pressure at which there were cases when the barrier had been put into action, as well as cases when this did not happen. Accordingly the larger number is the determinant value of the dynamic pressure since it represents the pressure over which the barrier had been put into action every time.

These numbers for the *EM Barbara* and for the *Dortmund* type barriers differ considerably. For the former, 1.3 kN/sq m is a sufficient pressure surely putting them into action, while as much as 11.0 kN/sq m are necessary to put into action the latter.

Under less favorable conditions — that is, when the barriers were arranged in front of the experimental surface gallery the respective values of the dynamic pressure were fixed at 3.0 kN/sq m for the *EM Barbara* barriers and 11.0 kN/sq m for the *Dortmund* barriers. On the basis of the data pertaining to the methane-and-coal-dust explosion disaster in the *Luisenthal* mine in the year 1962 it can be assumed that the *Dortmund* type barriers have served their purpose — that is, have stopped the explosion of coal dust in 10 particular cases but in many other cases they were of no effect. It is difficult to say exactly how many barriers failed but it is known, at any rate, that a certain number of barriers did fail and that this failure is responsible for the large number of casualties.

Investigations on the dependence of the dynamic pressure upon the flame velocity, discussed in Chapter 4, clearly indicate the possibility of explosions with a very weak dynamic pressure. Consequently it ought to be required as a condition for stone and water barriers that they could be put into action already with a dynamic pressure from 0.8 to 1.0 kN/sq m which corresponds to the flame velocity of 30 m/sec.

The *EM Barbara* type barriers can be put into action by the weakest coal dust explosions, particularly when the barrier frames are not less than 20 cm deep provided, of course, that they are correctly erected. The last mentioned condition means that the elements of a barrier should be free to be moved. If a barrier is fastened it cannot be put into action.

Investigations carried out in the *EM Barbara* show that velocities of a coal dust explosion flame of 30 m/sec, and even higher, can occur over short sections of mine workings but only with a great difficulty such velocities can persist over longer sections. If it happens that an explosion, from the place of its initiation to the place where the barrier is located, develops with a velocity of 30 m/sec the barrier can fail very easily when it cannot be put into action by the pressure corresponding to this velocity. The more so since the dust conditions in workings are not uniform and the coal dust deposited beyond the stone dust barrier can possess much higher explosive properties. The problem of weak explosions, as has already been pointed out in another chapter, is very important exactly on account of the difficulty — in certain cases — of stopping such explosions with barriers. Insufficient stone dusting can easily have the effect of making an explosion develop at a low velocity. This can make one think that it would be better not to dust the workings with stone dust at all because then an explosion, once it is iniciated, will develop with a violence sufficient to put a barrier into action. Obviously such a view would be wrong.

Turning back to the comparison between the *EM Barbara* and the *Dortmund* barriers it should be added that for both these types of barriers

(Table 9.1) the total time necessary to put the shelves into action is the same and, under experimental conditions, amounts to about 500 milliseconds.

The course of putting into action of the *Dortmund* barriers was examined with the aid of motion pictures analogously to the examinations made in respect of the *EM Barbara* barriers. The data included in Tables 9.1 and 9.2 is derived from these examinations.

The course of putting into action a limestone dust barrier of the *Dortmund* type 200×60 cm is shown in Fig. 9.5. The limestone dust load amounted to 160 kg.

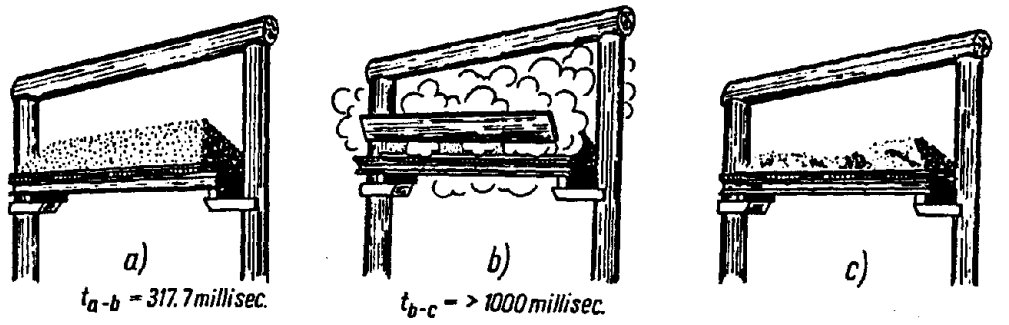


Fig. 9.5. The course of putting into action of the *Dortmund* type 200 × 60 cm stone dust (160 kg) barrier.

As can be seen in Fig. 9.5 not all of the limestone dust had been raised into the air from this barrier; a large portion of the dust was raised by the blast; a certain part of it by the lifting up of one of the longitudinal boards of the platform. But the boards of the platform were not thrown down and, as a result of this, a part of the dust remained on them. If the explosion were more violent the *Dortmund* barrier would have been put into action completely.

9.1.4.4. American barriers worked out by the Bureau of Mines. American barriers had been designed with a good knowledge of the way in which coal dust explosions develop on the basis of numerous investigations [144]. They were actually thoughtfully constructed barriers and, though they are not in use now, yet they deserve a short description especially on account of the fact that many interesting and instructive investigations were carried through in Poland on the effectiveness of these barriers [22].

The basic types of American barriers are shown in Figs. 9.6*a* and *b*. They are wooden troughs filled with stone dust. According to their constructors American barriers are not supposed to fall down under the impact of the blast but, after the props had been thrown out, they ought

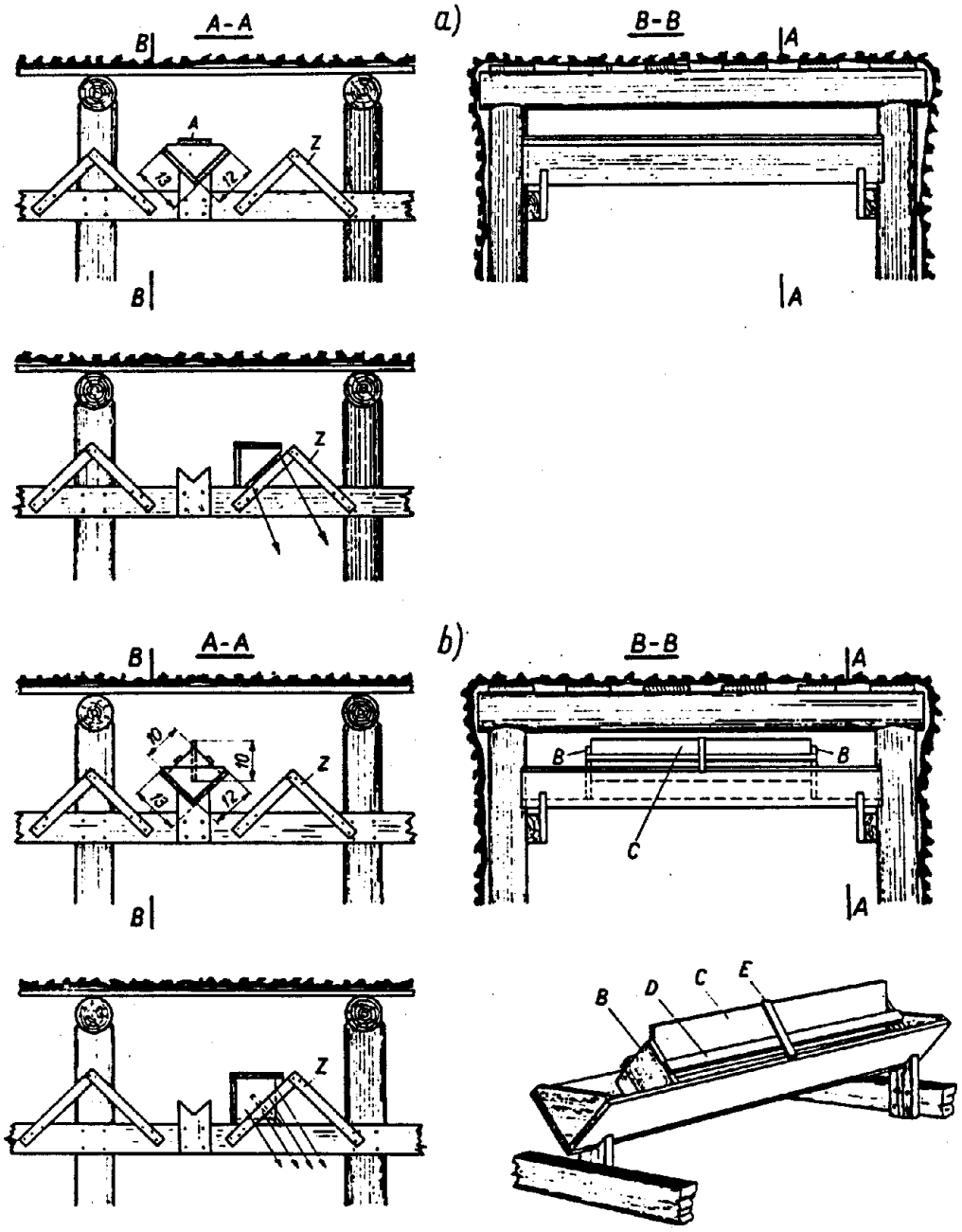


Fig. 9.6. American barriers: *a* — type *VB*; *b* — type *VV*.

to lean against the fenders (Figs. 9.6*a* and *b*). The constructors did not want the troughs to discharge at once the entire content of stone dust; they intended the troughs to pour their load out during a certain time

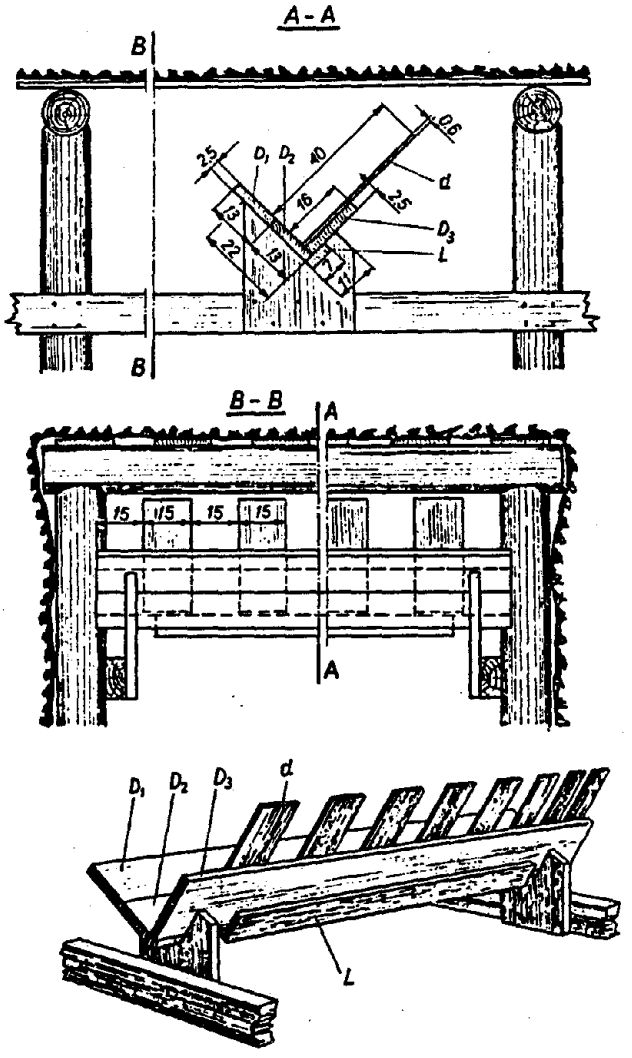


Fig. 9.7. A trough barrier of loose boards designed in the *EM Barbara*.

while the blast preceding the flame passes through the barriers. In this way the dispersion of stone dust was to be more thorough. In barriers of the *VB* type the longitudinal board *A* — partly screening the trough — was to serve this purpose; in the barrier of the slightly more complicated *VV* type this purpose was served by four elements (*B*, *C*, *D*, *E*).

According to investigations carried out in the experimental mine at *Bruceton* these barriers proved to be quite effective. Investigations carried out in the *EM Barbara* (discussed as tersely as possible at the end of this section) showed that with weaker explosions these barriers acted really effectively yet they failed manifestly with very strong explosions.

Polish investigations were carried out with the velocities of explosion flames ranging from 50 to 600 m/sec. Detailed examinations of the movements of the American troughs during explosions supplied the explanation why they are not effective with very strong explosions. Namely, the blast of a very strong explosion does not overthrow the trough but lifts it bodily up and presses it to the roof. In consequence the bulk of the stone dust at the most critical moment is screened by the boards of the trough. Only a complete destruction of the trough will cause the dispersion of the dust. But the belated action of the dust does not prevent the flame from passing the barrier. In the course of the Polish investigations described above attempts were made to improve the USA barriers but the results were not sufficiently good. Barriers designed in the *EM Barbara*, in which the troughs were constructed from loose boards (Fig. 9.7), proved to be very effective. However, when the production of these barriers had begun in mines mistakes were made in their construction and ultimately the *EM Barbara* ceased from recommending them for use. In their place the previously described *EM Barbara* barriers were introduced. The details of the investigations on the USA barriers are given in the publication [22]. The barrier shown in Fig. 9.7 is merely an example of the various types of barriers worked out in the *EM Barbara* of which only some were published.

9.1.5. The course of the operation of stone dust barriers during an explosion of coal dust

Assuming that a stone dust barrier is being properly put into action by a blast the effectiveness of the barrier's action depends on the following factors:

— The time interval between the moment at which the front of the blast reaches the barrier, thus initiating the process of putting the barrier into action, and the moment at which the front of the flame reaches the barrier; this interval of time is designated by the symbol t_p and is referred to, in short, as the time of putting the barrier into action; the value of t_p is a positive (plus) value when the barrier begins to be put into action before the front of the flame reaches the barrier, and it is a negative (minus) value when the flame precedes the putting of the barrier into action;

— The state of the dispersion of stone dust at the moment at which the flame reaches the barrier — that is, the concentration of stone dust at particular places in the cross section of the working;

— The size of the stone dust cloud — that is, the length of the section of the working occupied by this cloud;

— The position of the stone dust cloud in relation to the zone in

which the barrier is located at the moment at which the flame reaches the barrier.

The above parameters are the most important but, apart from these, other parameters play also a considerable role such, for instance, as the resistance offered by the barrier and its elements as well as by the stone dust in the shape of a very dense cloud.

These factors unquestionably influence very materially the course of an explosion not only as regards its thermal aspect; it should be underlined here that a sudden appearance of large masses of stone dust in front of a cloud of coal dust and in front of a flame offers a great inert resistance to the blast and this finds its expression — when the course of the explosion is recorded — in a considerable growth of the static pressure at the place of the barrier's location.

The stone dust cloud, formed at the barrier in consequence of it being put into action and the stone dust being dispersed by the blast, is not at all uniform in its composition — that is, it does not consist of stone dust alone. The blast that reaches the barrier and puts it into action represents actually the front of a cloud of coal dust raised up by the blast on its way. Thus the blast, that enters the zone in which the barrier is located and puts the barrier into action, brings coal dust along. The concentration of coal dust clouds varies considerably depending on the character of the explosion.

Moreover in the zone of the barrier coal dust can also be present when this zone had not been stone dusted. In such a case the blast raises up this coal dust also. As the result the cloud formed in the zone of the barrier, and usually carried by the blast beyond the place at which the barrier is located, is composed of stone dust and of coal dust. The extinguishing of the flame by the barrier depends, naturally, upon the concentration of stone dust in the cloud and on the size of the cloud. Of considerable importance also is the uniform concentration of stone dust in the entire cross section of the working a question already discussed in one of the previous chapters.

When the effectiveness of a barrier is considered all the factors mentioned above have to be taken into account.

What is the substance of the effect of the action of stone dust dispersed at the barrier is a question which ought to be explained now. The decisive role is played in this respect by the concentration of stone dust to a degree which deprives the environment of its explosive properties. According to explanations given previously coal dust is present in the environment mentioned above, but the action of the high temperature of the flame on this dust is manifestly impeded by the fact that the particles of coal dust are sheltered by the particles of stone dust, the

latter acting as a kind of a screen impenetrable to radiation. Though stone dust absorbs also certain quantities of the heat of the flame, yet the quantities so absorbed play a rather secondary role.

Also of great importance in the action of a barrier is the sudden discharge of a large mass of stone dust. It is understandable that the raising of a huge mass of stone dust by the blast impedes its progress taking up a part of its energy. The effect of a large quantity of stone dust being poured out from the barrier is clearly manifested in the growth of the static presure at the barrier's location.

9.1.6. The time t_p of putting a barrier into action

The time t_p of putting a barrier into action affects fundementally the barrier's effectiveness.

When the barrier is put into action after the flame had passed through it then — obviously — there is no question of the coal dust explosion being stopped by the barrier in question. On the other hand when the time of putting a particular barrier into action is too long this barrier can fail because it could happen that the stone dust will be dispersed before arrival of the flame; in such a case a large quantity of stone dust will be found on the floor.

To be most effective a barrier must be put into action at the most opportune moment for the dispersion of the entire load of stone dust throughout the whole cross section of the working at the exact time of the flame reaching the barrier. Such ideal conditions cannot be secured always in the case of barriers which are put into action by a blast on account of the great diversity of coal dust explosions. It happens now and again that with putting the barrier into action by a very strong initiator, the explosion develops relatively slowly and, in such a case, the time of putting the barrier into action can be very long. On the contrary an explosion could develop at once at such a high velocity that the time of putting the barrier into action might be too short to ensure the effectiveness of the action. In the described phenomenon of a great importance, naturally, is the distance between the barrier and the place at which the explosion had been initiated. The longer is the distance between the barrier and the place at which the explosion is initiated the more substantially the time of putting the barrier into action can grow. In such cases stone dust, dispersed from the barrier before the flame reached it, is sometimes raised into the air again by the blast preceding the flame. This will often suffice to stop the explosion particularly when the barrier occupies a sufficiently long section. One deals then with, as it were, a zone

very freshly spread with stone dust such a zone being also capable of preventing the propagation of an explosion.

A good illustration of the remarks made here is the fact that stone dust barriers frequently fail when located too near to places where explosions are initiated. Under such conditions the time of putting the barrier into action is too short.

In the light of the above considerations it can be perceived that a correct barrier, worthy of being recommended for use in mines, must act effectively when put into action within the limits of time corresponding to situations that are likely to occur in practice. It is also understandable that, in the course of investigations on various types of barriers in the *EM Barbara*, the time of putting the barriers into action had also been examined.

Under the experimental conditions in the *EM Barbara* the time of putting the barriers into action oscillated between a value approaching 0 and that of about 6.5 sec. It ought to be underlined that even longer times of putting barriers into action are possible; such occurrences are observed when barriers are located far from the places where explosions are initiated, particularly when the location of the barrier is separated from the place at which an explosion is initiated by a rather intricate network of workings.

It is interesting to note that in many of the tests made in the *EM Barbara* the barriers of the *EM Barbara* type were found to be very effective in spite of the fact that the beginning of the process of putting them into action coincided almost exactly with the barrier being reached by the flame — that is, the time of putting the barriers into action approached zero. Thus stone dust was being discharged at the moment of the flame passing the barrier. Undoubtedly of a considerable importance was the fact that a strong blast raises into the air an appreciable quantity of stone dust from the surface of the heap before the elements of the barrier are completely put into action; this is exactly what has been recorded during the investigations.

9.1.7. The various ways of stopping coal dust explosions by barriers

In the preceding section a mention was made of the ideal conditions for putting barriers into action. It is exactly depending on the fact how close to the optimal conditions proceeds the putting of a barrier into action, or how much these conditions deviate from the optimal ones, that the tests show either a stroppage of the explosion "on the spot" — that is, in the zone occupied by the barrier or a stoppage within a certain,

sometimes a considerable, distance beyond this zone. This depends on the position of the stone dust cloud already formed at the moment when the flame reaches it. If the flame reaches the stone dust cloud at a moment when this cloud still remains in the zone of the barrier the explosion becomes stopped on the spot.

The cloud of stone dust will be reached by the flame in the zone of the barrier if the discharge of the stone dust is still in progress when the flame reaches the zone; if the great mass of stone dust offers an inert resistance; and if the flame reaches the barrier very quickly. But when the blast contrives to carry the effective stone dust cloud beyond the zone of the barrier, when the flame is in pursuit of the cloud, the stoppage of the explosion is recorded at a certain distance from the zone of the barrier, not infrequently as far as 100 m beyond this zone. The total time of putting the shelves into action — that is, of the discharge of stone dust depends on the violence of the explosion. Investigations on the time of putting the shelves into action were carried out in the *EM Barbara* during methane explosion of high violence.

Under conditions of weak methane explosions the time of putting the shelves into action oscillated between 490 and 600 milliseconds approximately, depending on the breadth of the shelf, 35 or 50 cm, and on the depth of the frame from 10 to 20 cm.

In the case of a strong methane explosion the time of the discharge of stone dust amounted to 160 milliseconds. Under analogous conditions the times of the discharge of stone dust for *Dortmund* shelves 60 cm broad amounted to 540 and 110 milliseconds, respectively.

The approach to the optimal conditions of putting barriers into action is not only expressed in the stopping of an explosion on the spot but also in the minimal quantity of stone dust necessary to achieve this end. This quantity is, under such conditions, much smaller than the quantity required by regulations. The matter will be discussed in Section 9.4 where the principles on which triggered barriers are based are considered.

9.1.8. The notion of the volume concentration of stone dust on a barrier Q_v kg/cu m

One of the basic factors ensuring the effective action of a barrier, apart from the stone dust concentration in the formed cloud, is the length of this cloud. In other words of great importance are both the length of the barrier and the quantity of stone dust on the barrier in relation to the volume of the working in which the barrier is located.

The length of the barrier and the quantity of stone dust on the barrier are two magnitudes obviously bound up with each other.

In the *EM Barbara* the notion of the volume concentration Q_v was introduced — that is, the quantity of stone dust per unit of volume in the zone in which the barrier is located. The magnitude Q_v is obviously bound up with the quantity of stone dust on every shelf and with the distance between the shelves.

9.1.9. The notion of the quantity of stone dust Q kg/sq m on a barrier according to regulations

Mining regulations in almost all countries set forth the binding quantity of stone dust on a barrier as the value of Q expressing the quantity of stone dust per 1 sq m of the cross section area of the working.

According to regulations actually in force in Poland the value of Q amounts to 400 kg/sq m in methane seams and 200 kg/sq m in nonmethane seams.

The requirements in various countries are listed in Table 9.3. The quantities of stone dust on barriers required by regulations are usually much larger than those sufficient to stop a coal dust explosion. The discussion of this question in more detail will be done when the testing of barriers will be described. The minimum quantity of stone dust or water (kg/sq m), found experimentally to be sufficient to stop a coal dust explosion under given conditions, was denoted by the symbol Q_{II}. The value of Q_{II} has been found to be lower, as a rule, than the value of Q.

The use of the quantities of stone dust exceeding the experimental findings is necessary in order to make sure that there is a sufficient safety margin the more so since, under unfavorable conditions as had been explained in Section 8.7, stone dusting does not provide a sufficient safety margin even if it is done in strict compliance with regulation requirements. It is, therefore, necessary for the barriers to be capable of surely stopping a coal dust explosion in every case of such an explosion occuring in a mine.

In practice it is impossible to foresee the character of a concrete coal dust explosion; consequently the regulations cannot be made to correspond to the degree of the seriousness of the explosion hazard. In many countries as, for example, in Poland, regulations require smaller quantities of stone dust in nonmethane than in methane seams. This is based on the presumption that in a nonmethane seam an explosion will be easier to stop. Strictly speaking, however, this contention has not been properly demonstrated. The probability of a coal dust explosion in a methane seam is considerably greater than in a nonmethane seam since the most common factor initiating coal dust explosions (methane) is absent from the last named seam. Nevertheless, a coal dust explosion in nonmethane seams could be initiated by

flammable fire gases and these can act as a very strong explosion initiator in no way weaker than a methane initiator. Besides, if in a nonmethane seam a dust explosion were to develop in a zone of pure fine coal dust the explosion initiator thus created would be a very strong one; as a matter of fact it could be considerably stronger than an initiator consisting in the explosion of even a large volume of an explosive mixture of methane. As an example the initiator 30mPII, used in the *EM Barbara*, can be cited: it is stronger thant the 50 cu m CH_4 initiator.

Table 9.3

A Schedule of the Quantities of Stone Dust on Barriers Required under Regulations in Various Countries

Country	Name of the barrier	Quantity of stone dust kg/sq m
Great Britain	primary	100
	secondary	100
	light	100–200
	heavy	400
Chechoslovakia	auxiliary	200
	main	400
France	—	400
German Democratic Republic	auxiliary	100
	main	400
Federal Republic of Germany	—	400
Poland	nonmethane seams:	
	auxiliary	200
	main	200
	methane seams:	
	auxiliary	400
	main	400
USSR	—	400

The use of smaller quantities of stone dust on barriers in nonmethane seams is being explained additionally by the fact that in a methane seam one should always take into account the presence in the air of certain quantities of methane in the free cross section of the working and the presence of methane behind the support. Naturally the hazard of this kind does not appear in a nonmethane seam. Taking into account all the above mentioned considerations and, particularly, the fact that the quantity of stone dust prescribed by regulations gives, in a great majority of cases, a large safety margin, it is possible to conclude that a smaller quantity of stone dust required by regulations on barriers in nonmethane seams than the quantity required in methane seams finds a practical justification.

Recapitulating the above short considerations, concerning the considerably larger quantities of stone dust required by regulations than the quantities indicated by the results of the majority of experiments, it ought to be stated that in experiments dry stone dust is used of a very good dispersibility, while in practice one deals with a dust the dispersibility of which deteriorates with the passage of time. Although, according to regulations, a periodical replacement of stone dust on barriers is required yet, even with a careful fulfilment of regulation requirements, there always will be a certain period of time during which stone dust on a barrier will be less effective on account of being less dispersible.

9.1.10. Dependence of the effectiveness of stone dust barriers upon the violence of the explosion and upon the distance between the barrier and the place of the initiation of the explosion in a straight gallery [42]

9.1.10.1. General information. Many investigations were devoted in the *EM Barbara* to this very important and fundamental problem. Only a summary of the results of these investigations is given in this book.

To begin with it should be underlined that, as has been demonstrated in numerous tests, the growth of the effectiveness of the action of stone dust barriers is not at all directly proportional to the violence of the explosion, or to the reduction of the distance between the barrier and the place of the initiation of the explosion.

In the course of investigations on the influence of the violence of explosions (expressed in terms of the flame velocity) upon the effectiveness of barriers it has been established that it diminishes under extreme conditions — that is, when explosions are either very strong or particularly weak. Violent explosions with relatively high velocities, but still considerably below 1000 m/sec, can be stopped relatively easily. It should be explained that, when reference is made here to a more or less effective action of barriers what is meant by it, in the first place, is the quantity of stone dust on a barrier sufficient to stop an explosion but also the probability of the barrier acting effectively with the quantities of stone dust corresponding to regulation requirements.

Naturally the effectiveness of a barrier must be dependent upon its distance from the face of the working — that is, from the place of the initiation of the explosion. Further on, the distance of the barrier from the face of the working will be understood to denote the distance between the first shelf and the place of the initiation of the explosion. The expression referring to the face of the working has been adopted because, in the experiments, explosions had been initiated at the faces of the experimental galleries. With the change of the barrier's distance from the gallery's face

the time of putting the barrier into action t_p, for the given explosion, will also change. The magnitude t_p has a strong influence on the barrier's effectiveness (Section 9.1.6).

It is understandable that the state of formation of a stone dust cloud in consequence of the barrier being put into action must depend upon t_p. For this reason barriers located close to the working face, for example, at a distance of 20 m, fail in a majority of cases.

The time of putting a barrier into action depends not only on the distance of the barrier from the face of the working but also on the explosion initiator and on the course of the explosion. Accordingly it was necessary to carry out the pertinent investigations under conditions of explosions varying in respect of their initiators as well as in respect of their courses.

The effectiveness of barriers in the case of particularly weak explosions is a special problem which will be discussed separately. All the results given here refer to the testing of the *EM Barbara* type barriers 35 or 50 cm broad. The tests were carried out in the 400 m underground experimental gallery of a 7.5 cm cross section area.

It should be explained that the cases of stopping a coal dust explosion "on the spot" include the cases in which the flame did not reach the distance of 20 m beyond the barrier.

In the tests seven different kinds of explosions were arranged for. Stone dust barriers were located at the following distances from the gallery's face: 20, 40, 60, 80, 100, 160, 200, 220, 240, 260, 280, and 320 m.

The results of the tests were made out in the form of a graph in which, on the x-axis, are given the distances of the barrier from the gallery's face and on the y-axis the quantities of stone dust on the barrier (kg/sq m) sufficient to stop an explosion. In the outcome curves were obtained which clearly illustrate the influence of the distance between the barrier and the gallery's face on the effectiveness of the barrier for a given kind of explosion.

9.1.10.2. Stopping weak explosions when the very strong initiator 30mPII was used. In these tests the d85 coal dust had been used with the content of incombustible solid matter $n = 67.5$ percent under the easiest dispersion conditions.

Explosion flame velocities before the barrier in this series of tests oscillated between 100 and 280 m/sec depending on the distance between the barrier and the gallery's face. The mean flame velocity amounted to about 150 m/sec.

The results obtained are presented in a graphic form in Fig. 9.8. Two curves are shown in the figure: a solid-line curve *1* representing the stoppage of explosions on the spot, and a broken-line curve *2* representing

the stoppage of explosions at a distance up to about 100 m beyond the barrier.

Noteworthy is the possibility of stopping this kind of explosions already at a distance of 20 m from the face of the gallery with $Q = 100$ kg/sq m. As the distance between the barrier and the gallery's face grows

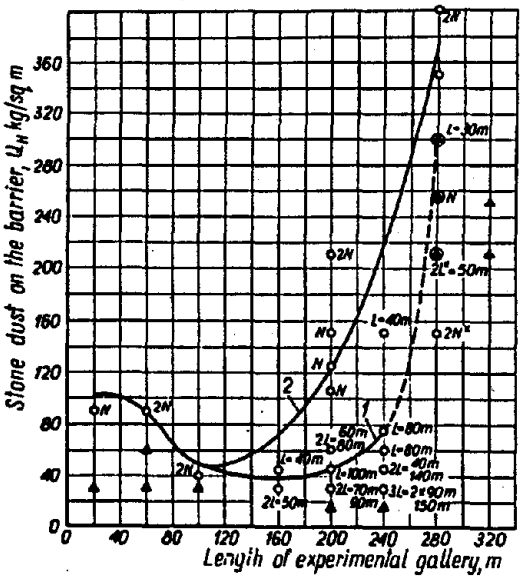


Fig. 9.8. A diagram of the effectiveness of stone dust barriers depending on the distance between the barriers and the gallery face; coal dust d85, $n = 67.5\%$, initiator 30mPII: *1* — stopping explosion on the spot; *2* — stopping explosion beyond the barrier. Explanations: *oN* — stopping explosion "on the spot" in the zone of the barrier or ~ 20 m beyond the barrier; *oL* — stopping explosion $L = \ldots$ m beyond the barrier; ▲ — nonstopping explosion (propagation of explosion through the barrier); ⓐ — stopping explosion or propagation of explosion under identical conditions: × — in the zone of the barrier stone dust had been added to the dust under examination ($n = 67.5\%$) to a content of $n = 90\%$.

the quantity of dust Q_H on the barrier, able to stop an explosion, diminishes at first; at the distance of 100 m from the face it amounts to about 40 kg/sq m only and then, for curve *1*, a sudden growth of Q_H is observed when for curve *2* this growth is very slow in the beginning. Both curves show that at a distance over 230 up to 270 m the quantity of stone dust required by regulations for a barrier in a nonmethane seam $Q = 200$ kg/sq m becomes insufficient. As an illustration of this series of tests in Fig. 9.9 a diagram is presented of the explosion No. 60 stopped by a barrier with $Q = 150$ kg/sq m at a distance of 240 m from the face of the gallery.

9.1.10.3. Stopping weak explosions initiated by a strong firedamp explosion ignited by 750 g of gunpowder. Tests of this series differed from

the ones previously discussed by the use of 50 cu m CH_4 (9.5 percent) or 100 cu m CH_4 as the initiators. Conditions of dispersion were again the easiest.

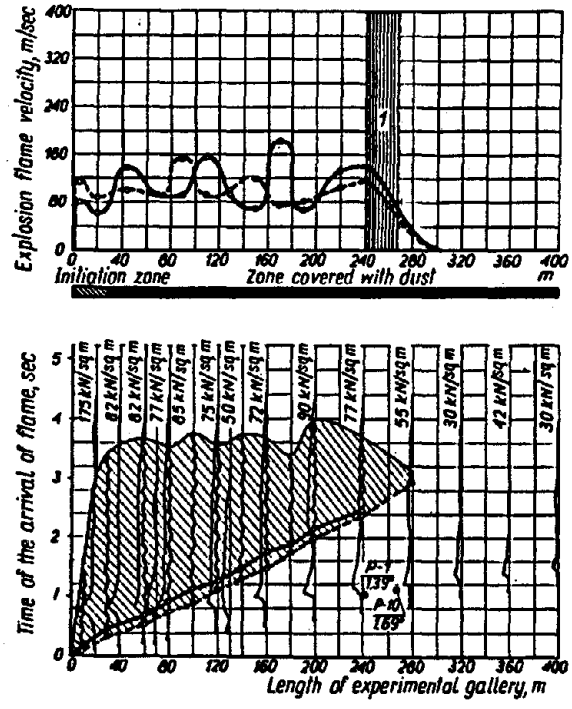


Fig. 9.9. A diagram of the explosion No. 60 of the d85 coal dust, $n = 67.5\%$, initiator 30mPII; *1* — the barrier of 10 shelves, 1125 kg of stone dust, $Q = 150$ kg/sq m stopped this explosion almost on the spot. Symbols as in Fig. 6.4.

The results of the tests are presented in a diagram shown in Fig. 9.10. This diagram resembles very much the diagram shown in Fig. 9.8 and, therefore, there is no necessity of discussing it. As an illustration for this series of tests in Fig. 9.11 a graph is given of the explosion No. 72 stopped by a barrier located at the distance of 200 m from the face of the gallery with the quantity of stone dust $Q = 60$ kg/sq m. In this figure a very characteristic abrupt rise of the flame velocity curve near the gallery's face, caused by the explosion of 100 cu m CH_4, is observed.

Before reaching the barriers flame velocities differed but slightly with either of the two initiators (50 and 100 cu m CH_4); they oscillated between 100 and 160 m/sec, the mean velocity amounting to 135 m/sec.

9.1.10.4. Stopping very violent explosions started by a very strong 30mPII initiator. Coal dust *d*85, with incombustible solid matter content

$n = 50$ percent, was used in the tests; dispersion conditions were the easiest.

The coal dust used corresponds to the coal dust formed in mines in which the workings had not been properly stone dusted. Explosions were very violent. Flame velocities before reaching the barrier oscillated between 60 m/sec at the distance of 40 m and 940 m/sec at the distance of 240 m (depending on the distance from the gallery's face); the mean velocity amounted to 290 m/sec.

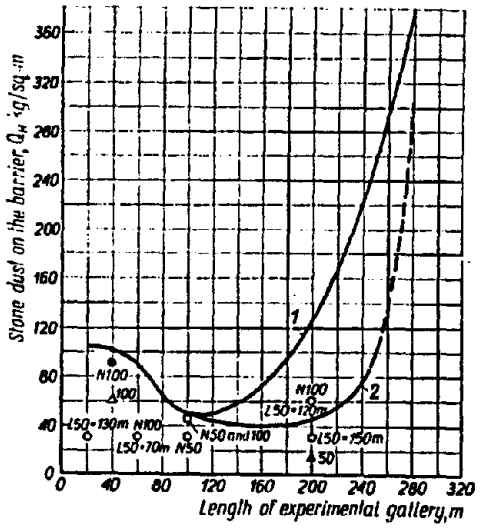


Fig. 9.10

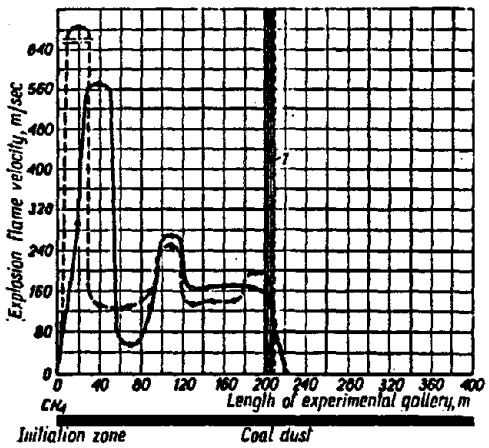


Fig. 9.11

Fig. 9.10. A diagram of the effectiveness of stone dust barriers depending on their distance from the face of the gallery: coal dust d85, $n = 67.5\%$, initiator 50 or 100 cu m CH_4 (9.5%), ignition with 750 g of gunpowder. Explanations: number 50 with symbol indicates initiator 50 cu m CH_4; number 100 with symbol indicates initiator 100 cu m CH_4; ●, △ — firedamp ignited with electrical detonator at the paper partition.

Fig. 9.11. A diagram of the explosion No. 72 of the d85 coal dust, $n = 67.5\%$, initiator 100 cu m CH_4, ignition with 750 g of gunpowder; *1* — the barrier of 4 shelves, 450 g of stone dust, $Q = 60$ kg/sq m stopped this explosion on the spot.

The findings of this series of tests are presented graphically in Fig. 9.12. Only one curve is shown representing the stoppage of explosions on the spot. The shape of this curve is very characteristic. It indicates clearly that the optimal location of the barrier is at the distance of about 100 m from the gallery's face. At this point $Q = 75$ kg/sq m of stone dust is quite sufficient to stop very violent explosions. With the shifting of the barrier in the direcion of the face of the gallery the magnitude of the barrier, capable of stopping an explosion, grows very distinctly. Likewise,

the shifting of the barrier beyond 100 m from the face of the gallery necessitates the use of a decidedly heavier barrier. In spite of their violence the explosions in question are surely stopped by barriers with Q below 200 kg/sq m (the value prescribed by regulations for nonmethane seams)

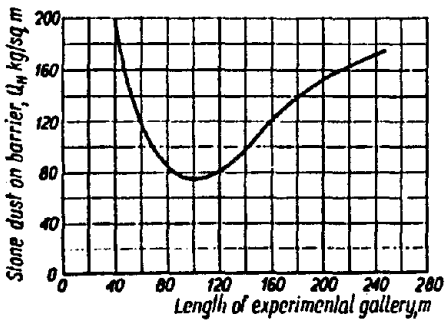


Fig. 9.12. A diagram of the effectiveness of stone dust barriers depending on their distance from the gallery's face; coal dust d85, n = 50%, initiator 30mPII.

provided that the barriers are located at distances from 60 to 240 m from the face of the gallery. Graphs illustrating this very interesting series of tests are given in Fig. 9.13 showing the course of two explosions.

In Fig. 9.13*a* a graph is given of explosion No. 99 not stopped by the barrier located at the distance of 240 m from the gallery's face with a load of stone dust Q = 120 kg/sq m. This explosion has been stopped at the distance of 380 m from the face but then only by a storied protecting barrier containing a load of stone dust amounting to Q = 135 kg/sq m. It ought to be explained that protecting barriers had been installed in order to prevent damages on the surface.

In Fig. 9.13*b* a graph is given of explosion No. 222 stopped by the barrier located at the same distance of 240 m from the face of the gallery but slightly heavier (Q = 135 kg/sq m). Very considerable acceleration of the flame velocity as well as very high velocities of the flame, before its arrival to the barrier, are noticeable on both graphs and in the graph shown in Fig. 9.13*a* also beyond the barrier. For the sake of precision it should be stated that the velocity of 2500 m/sec, registered photoelectrically according to the graph given in Fig. 9.13*a* beyond the barrier, is a very questionable value and that the velocity of about 1000 m/sec, registered by the detonator method, ought to be regarded as a rather more reliable one.

The Fig. 9.13*b* contains also a diagram of time — distance. This diagram shows that the shelves marked by symbols *P-1*, *P-4*, *P-9* were put into action just before the passage of the flame. The time of putting the shelves into action amounted to a couple of dozen milliseconds.

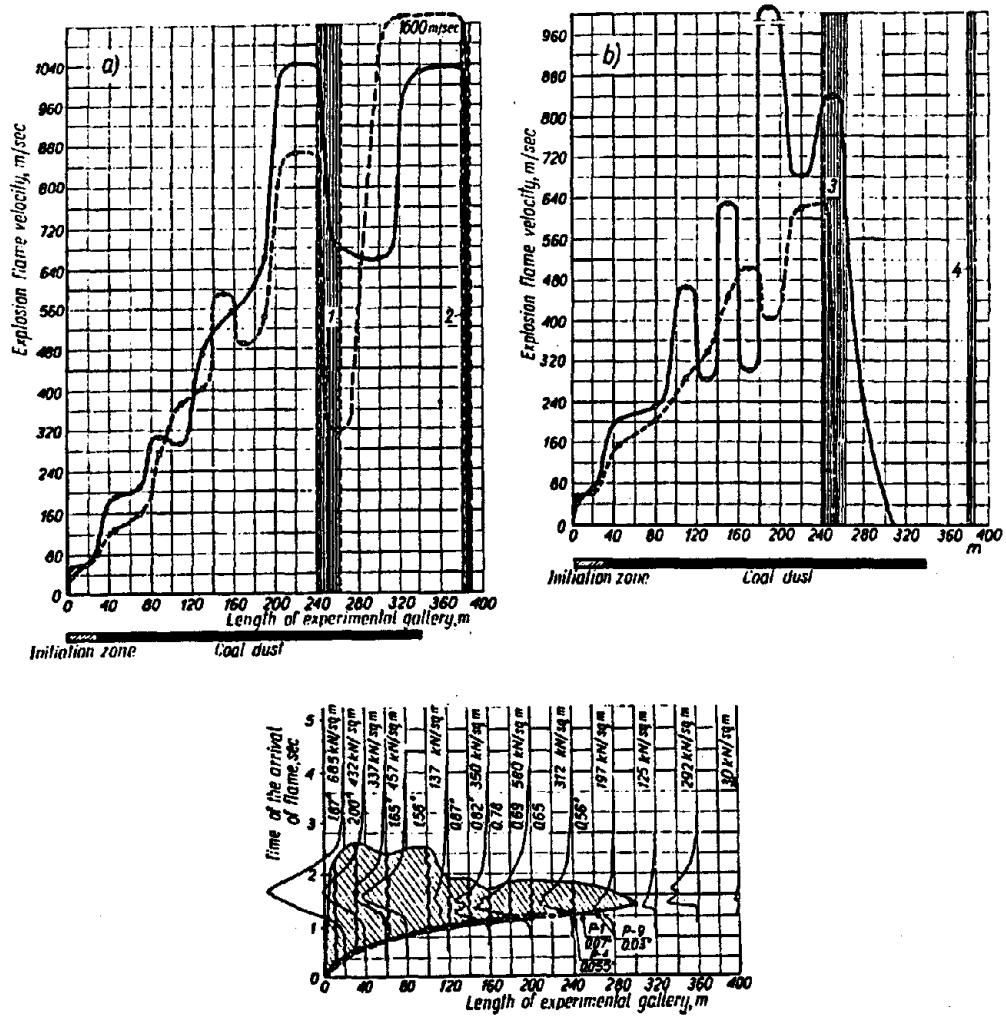


Fig. 9.13. Diagrams of explosions: *a* — explosion No. 99 of the *d*85 coal dust, $n = 50\%$, initiator 30mPII; *1* — the barrier of 8 shelves, 900 kg of stone dust, $Q = 120$ kg/sq m did not stop the explosion which has been stopped by *2* — the storied protecting barrier 3 × 3, 1012 kg of stone dust, $Q = 135$ kg/sq m at the distance of 380 m from the gallery's face; b — explosion No. 222 of the d85 coal dust, $n = 50\%$, initiator 30mPII; *3* — the barrier of 9 shelves, 1012.5 kg of stone dust, $Q = 135$ kg/sq m stopped this explosion almost on the spot; *4* — storied protecting barrier, 3 × 3, 1012.5 kg of stone dust, $Q = 135$ kg/sq m. Symbols an in Fig. 6.4.

9.1.10.5. Stopping very violent explosions initiated by a strong explosion of methane 50 cu m CH_4 — ignition 750 g of gunpowder. In this series of tests the *d*25 coal dust was used containing the natural quantity of incombustible solid matter $n \approx 20$ percent; dispersion conditions were the easiest. The experiments corresponded to a situation in the mining practice

created in the outcome of a complete failure to comply with the regulation requirements concerning the dusting of workings with stone dust.

Explosions in this series were also very violent the maximum velocities of the explosion flame before reaching the barrier oscillating between 100 m/sec at the distance of 60 m and up to 1200 m/sec at the distance of 240 m, depending on the distance between the barrier and the gallery's face; the mean flame velocity amounted to 400 m/sec.

In Fig. 9.14 a graphic presentation is given of the findings of the tests in the shape of two curves — a broken-line curve *2* representing the stoppage of coal dust explosions on the spot and a solid-line curve *1* representing the stoppage of coal dust explosions at a certain distance beyond the barrier.

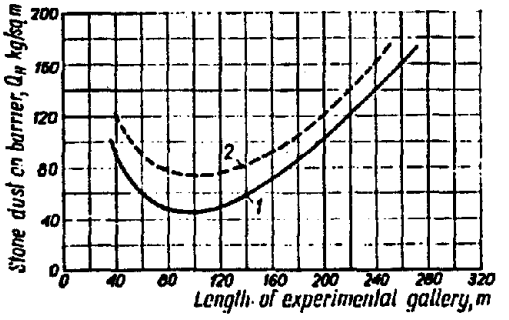


Fig. 9.14. A diagram of the effectiveness of stone dust barriers depending on their distance from the gallery's face; the $d25$ natural coal dust, $n=20\%$, initiator 50 cu m CH_4 (9.5%), ignition 750 g of gunpowder: *1* — corresponds to direct results of the tests; *2* — plotted with a higher confidence interval.

The solid-line curve gives a sufficiently dependable presentation of the effectiveness of barriers, the broken-line curve presents this effectiveness with a higher confidence level.

For comparison with other series of experiments the solid-line curve will serve quite well. This curve shows the optimum place for the location of the barrier analogously to the previously discussed tests — that is, at a distance of about 100 m from the gallery's face. Both, for distances nearer to the face and farther from it this curve ascends and descends less abruptly than that shown in Fig. 9.12.

By comparing the curves shown in Fig. 9.14 with those in Fig. 9.12 it is found that, under the conditions in which tests were carried out, in spite of the great violence of the explosions, these explosions, in the series here discussed, were stopped much easier than in the case shown in Fig. 9.12 in which the results of the series of experiments discussed in Section 9.10.4 were presented.

As an example illustrating the described tests in Fig. 9.15 a graph is given of explosion No. 236 stopped by the barrier $Q_{II} = 120$ kg/sq m at the distance of 240 m from the gallery's face. The graph shows the characteristic very considerable acceleration of the flame and a very high velocity of the flame before it reached the barrier. This explosion was stopped almost on the spot.

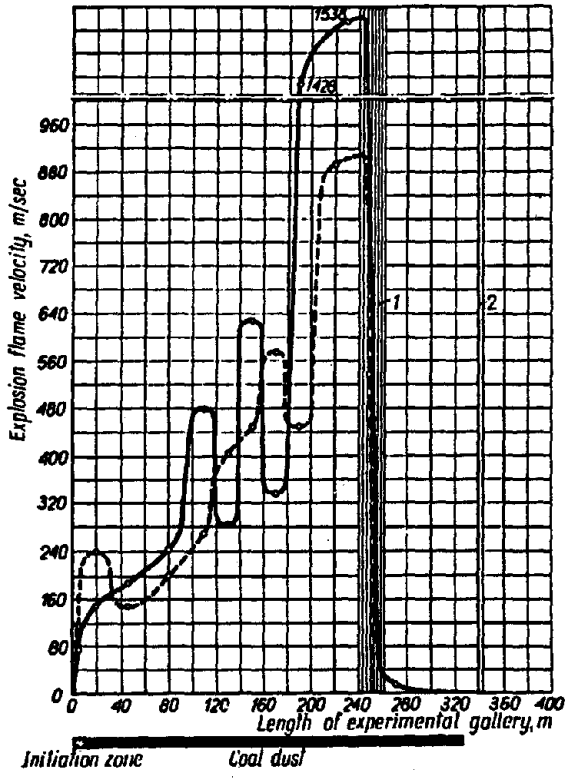


Fig. 9.15. A diagram of explosion No. 236 of the d25 natural coal dust, $n = 20\%$, initiator 50 cu m CH_4 (9.5%); *1* — the barrier of 8 shelves, 900 kg of stone dust, $Q = 120$ kg/sq m stopped this explosion almost on the spot; *2* — storied protecting barrier, 2 × 3, 675 kg of stone dust, $Q = 90$ kg/sq m.

9.1.10.6. Stopping violent explosions initiated by a weak explosion of methane 50 cu m CH_4; ignition close to a paper partition. In these tests the natural d25 coal dust had been used; the dispersion conditions were the easiest. Explosions were initiated by exploding 50 cu m CH_4. The essential difference between this test and the former tests consisted in the use of the electric igniter close to the paper partition. This initiator is much weaker than the one used in the tests described in Section 9.1.10.5. Under these conditions the blast of the methane explosion is very mild.

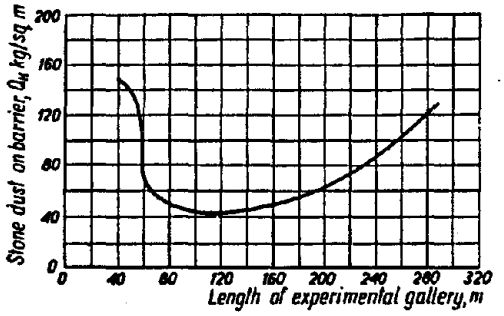


Fig. 9.16. A diagram of the effectiveness of stone dust barriers depending on their distance from the gallery's face; the d25 natural coal dust, $n = 20\%$, initiator 50 cu m CH_4 (9.5%); ignition with an electric detonator close to the paper partition.

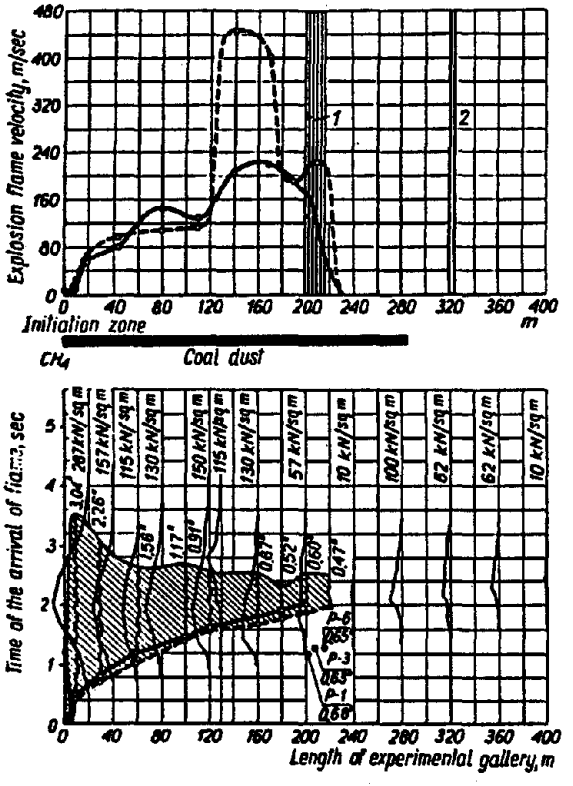


Fig. 9.17. A diagram of explosion No. 240 of the d25 natural coal dust, $n = 20\%$, initiator 50 cu m CH_4 (9.5%); ignition with an electric detonator close to the paper partition; *1* — the barrier of 6 shelves, 675 kg of stone dust, $Q = 90$ kg/sq m stopped this explosion; *2* — storied protecting barrier, 2×3, 675 kg of stone dust, $Q = 90$ kg/sq m. Symbols as in Fig. 6.4.

Coal dust explosions become more violent only at a certain distance from the gallery's face. Flame velocities before reaching the barier oscillated, depending on the distance from the face, between 80 m/sec at the distance of 40 m and 720 m/sec at the distance of 240 m, the mean velocity amounting to 190 m/sec. Explosions of this type are very likely to occur in practice.

The explosion series discussed here differs materially from explosions described in Sections 9.1.10.4 and 9.1.10.5 in that the acceleration of the flame's velocity in the beginning of the route of the explosion is relatively low. However, after a certain run, these explosions can become as violent as the ones described in the above mentioned sections. The results of the tests are presented graphically in Fig. 9.16.

Characteristically the descent of the curve is very steep between the distances of 40 and 60 m. This is strictly bound up with the use of a weak initiator. The zone of the optimum effectiveness of the barrier extended from 160 to 200 m from the gallery's face so that it was very long in comparison with the findings of previous tests. Beyond the distance of 200 m from the face of the gallery the curve of the effectiveness of barriers shows a clear tendency to rise. As an example illustrating this series of experiments in Fig. 9.17 a graph is given of explosion No. 240 stopped on the spot by the barrier $Q_{II} = 90$ kg/sq m. The graph shows a slow increase in the flame's velocity and also the fact that the shelves were put into action in a considerably longer interval of time, after the arrival of the flame, in comparison with former experiments; t_p in this case amounts to about 0.68 sec.

9.1.10.7. Stopping violent explosions started by a weak initiator 4mPII. The initiator mentioned above represents the explosion of pure $d85$ coal dust on the 4 m zone at the gallery's face ignited by a shot of 750 g of gunpowder.

In these tests the natural $d25$ coal dust was used ($n = 20$ percent) and the easiest dispersion conditions were procured. Under such conditions the explosions exhibited at first a relatively slight acceleration of the flame in consequence of the weakness of the initiator. However, beyond the distance of 100 m, the acceleration grew very distinctly and ultimately the explosions became violent. The velocity of the flame, before the flame reached the barrier, oscillated between 20 m/sec at the distance of 40 m and 760 m/sec at the distance of 260 m, the mean velocity amounting to 170 m/sec. Thus the course of the explosions was similar to that described in Section 9.1.10.6.

The results of the tests are presented graphically in Fig. 9.18. The shape of the curve shows a certain similarity to the curve given in Fig. 9.16. The abrupt decline of the value of Q_{II} is visible when the barrier

becomes shifted from the distance of 40 m to that of 60 m. The optimum zone for the barrier's location lies at the distance from 140 m to aproximately 200 m from the face of the gallery.

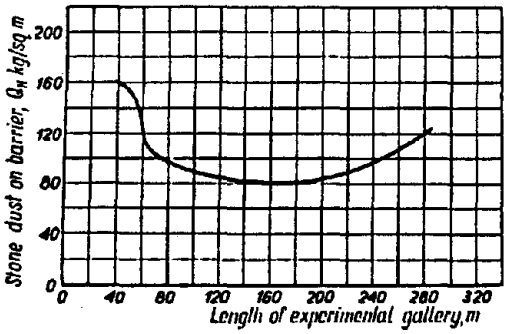


Fig. 9.18. A diagram of the effectiveness of stone dust barriers depending on their distance from the gallery's face; the d25 natural coal dust, n = 20%, initiator 4mPII.

Generally it can be admitted that the stoppage of an explosion is certain with regulation quantities of stone dust on a barrier as required in the case of nonmethane seams, when the distance of the barrier from the face of the gallery is from 60 to 260 m. As an illustration exemplifying this series of tests, devoted to the determination of the effectiveness of barriers under the conditions described above, a graph is given in Fig. 9.19

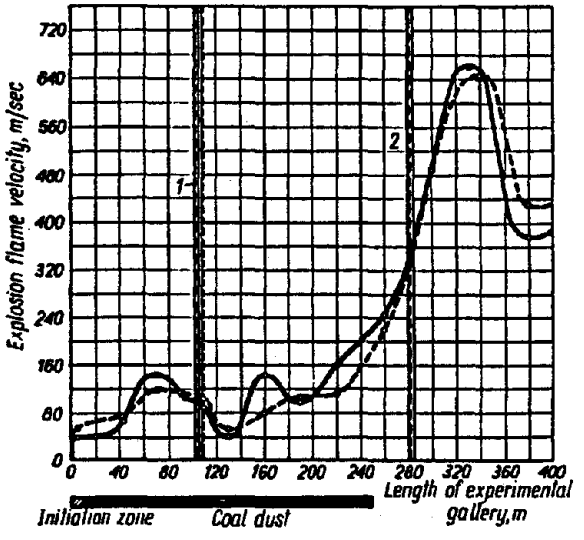


Fig. 9.19. A diagram of explosion No. 131 of the d25 natural coal dust, n = 20%, initiator 4mPII; *1* — the barrier of 3 shelves, 337.5 kg of stone dust, Q = 45 kg/sq m did not stop this explosion; *2* — storied protecting barrier, 2 × 3, 675 kg of stone dust, Q = 90 kg/sq m.

of explosion No. 131 not stopped by the barrier $Q = 45$ kg/sq m located at the distance of 100 m from the gallery's face. It ought to be stated that the time of putting the shelves into action had been correct, oscillating from 0.48 to 0.6 sec. It is a very characteristic feature of this explosion that it was not stopped by the three-story protecting barrier (2×3, $Q = 90$ kg/sq m) placed at the distance of 280 m from the gallery's face. Even much more violent explosions had been usually stopped quite well by protecting barriers of this kind.

9.1.10.8. A summary of the results of investigations on the effectiveness of stone dust barriers of the *EM Barbara* type as depending on the violence of explosions and on the distance between the barrier and the place at which the explosion is initiated. Investigations which were carried through with reference to six different kinds of explosions had shown that, generally the dependence of the effectiveness of barriers upon their distance from the gallery's face varies according to the type of the explosion. The process of stopping an explosion by means of a barrier obviously depends also on the nature of the explosion and this dependence is a complicated one.

In the course of these investigations it has been found that for each of the examined types of explosions there exists the optimal zone for the location of the barrier. Of considerable interest and rather noteworthy is the fact that in every case the distance of 100 m, from the place at which the respective explosions were initiated, is found lying within the optimal zone.

One can, therefore, generalize the ascertainment that the distance of 100 m from the gallery's face, or from any other place at which an explosion is likely to be initiated, is the most advantageous distance for the location of a barrier. Naturally it is difficult in practice to keep barriers permanently at this distance from gallery faces. The barriers placed at this distance have been known to stop explosions with the quantities of stone dust Q_{II} from 40 to 80 kg/sq m. These quantities are appreciably smaller than these required by regulations.

Barriers placed at distances from 60 to 200 m from the gallery's face stopped explosions assuredly, in all cases, with quantities of stone dust smaller as a rule than the quantities required by regulations for non-methane seams (200 kg/sq m). It is possible to take for granted, therefore, that regulations ensure a large safety margin especially in the case of methane seams. At any rate barriers should not be located farther than 200 m from the places at which explosions are likely to be initiated. For it had been established in the course of the investigations that, in the case of certain types of explosions, the location of the barrier at a distance close to 300 m from the gallery's face resulted in the necessity of having the

Table 9.4

A Summary of the Results of the Comparative Tests of the Effectiveness of Water Barriers and of Stone Dust Barriers Located both in the Rectilinear 400 m Gallery and beyond Gallery Bends

Kind of barrier	Gallery	Barrier location m	Flame velocity m/sec	t_ρ sec	Q_{II} kg/sq m	Comparative effectiveness of barriers
H_2O w	rectilinear	100	260	0.14	75	pl
s. d.		100		0.43	75	
H_2O w	rectilinear	40	110	0	90	pl
s. d.		40		0.13	90	
H_2O w		60	250	0	30	pl
s. d.		60		0.22	30	
H_2O w	rectilinear	100	180	0.40	45	
s. d.		100		0.45	45	pl
H_2O w	rectilinear	60	50	1.36	90	
s. d.		60		0.24	90	pl
H_2O w	rectilinear	60	130	0.03	60	=
s. d.		60		0.10	60	=
H_2O w	double bend	40	55	0.52	~ 300	
s. d.		40		0.66	~ 120	2.5 ×
H_2O w		60	90	0.92	~ 120	
s. d.		60		0.64	~ 100	1.2 ×
H_2O w	double bend	40	160	0	> 240	
s. d.		40		0	200	> 1.2
H_2O w		80	320	0.16	~ 100	pl
s. d.		80		0.23	~ 100	
H_2O w	single bend	123	83	2.84	90	?
s. d.		180	440	1.19	165	
		220	715	0.41	90	
H_2O CS	rectilinear	60	120	0.17	108	=
s. d.		60			100	=
H_2O CS		100	120	0.48	< 162	
s. d.		100			45	?
H_2O CS		200	380	0.59	< 162	
s. d.		200			60	?
H_2O CS	rectilinear	200	550	0.59	< 240	
s. d.		200			120	?
H_2O CS	double bend	40	190	0.08	> 162	
s. d.		40			90	> 1.8
H_2O CS		100	360	0.07	< 144	
s. d.		100			45	?
H_2O CS	single bend	220	740	0.01	220	
s.d.		220			220	> 1 ×
H_2O PE	rectilinear	40	130	0.13	> 160	
s.d.		40			150	> 1.1 ×

value of $Q \approx 400$ kg/sq m to stop the explosion which means that, under such conditions as those discussed in Section 9.1.10.6, in nonmethane seams barriers carrying the prescribed load of stone dust do not ensure the stoppage of explosions. In methane seams the regulation quantities of stone dust on a barrier provide in such cases only a very narrow margin of safety.

It should be stated that the investigations discussed here were carried out with the use of limestone dust in a proper condition — that is, its dispersibility being very good. With the passage of time during which the dust lies deposited on the barrier its dispersibility deteriorates. Therefore, one should not conclude from the generally very favorable results of the investigations described here that the regulation requirements, as regards the quantity of stone dust on barriers, provide too high a level of confidence in the matter of the stoppage of explosions. The results of the investigations discussed here are summarized in Table 9.4. In this table the symbol Q_n denotes the quantity of limestone dust on a barrier sufficient to stop a coal dust explosion in given conditions.

9.1.11. The influence of bends of galleries on the effectiveness of stone dust barriers

9.1.11.1. General information. In the mining practice the necessity frequently arises of placing main, and not infrequently also auxiliary, barriers beyond the bends of galleries. For this reason in the *EM Barbara* [43] as well as, on a smaller scale, in the Federal Republic of Germany, in the *EM Tremonia* [102] investigations have been carried out on the effectiveness of barriers beyond gallery bends.

The most important results of investigations, which were carried out in the *EM Barbara* very systematically, are given below.

9.1.11.2. Investigations on the effectiveness of barriers placed beyond two bends of the same cross section area. Explosions were initiated in the gallery parallel to the 400 m experimental gallery (see Fig. 2.1). The effectiveness of barriers was tested beyond the two-directional bend of the galleries with reference to four different kinds of explosions.

As the effectiveness of barriers was tested from the viewpoint of its dependence upon the course of the explosion, as well as upon the distance of the barrier from the place at which explosions were initiated, the results of the tests have been compared with the results obtained in the rectilinear gallery described in Section 9.1.10.

The stopping of weak explosions started by the strong explosion initiator 30mPII. In these investigations the d85 coal dust was used in which the content of incombustible solid matter $n = 67.5$ percent. It should

Table 9.4 (continued)

Kind of barrier	Gallery	Barrier location m	Flame velocity m/sec	t_p sec	Q_{II} kg/sq m	Comparative effectiveness of barriers
H_2O PE		60	140	0.40	> 80	
s.d.		60			60	> 1.3×
H_2O PE		100	100	0.72	45	=
s.d.		100			45	=
H_2O PE		160	360	0.48	65	
s.d.		160			50	?
H_2O PE	rectilinear	60	100	0.29	120	=
s.d.		60			120	=
H_2O PE		100	120	0.80	75	=
s.d.		100			75	=
H_2O PE	double bend	40	340	0.07	> 120	
s.d.		40			120	> 1×
H_2O PE		60	360	0.08	160	=
s.d.		60			160	=

The meaning of denotations:

H_2O w — a water barrier consisting of trough type containers;

H_2O CS — a water barrier consisting of polystyrene containers of Czechoslovakian manufacture;

H_2O PE — a water barrier consisting of polyethylene bags manufactured in the German Democratic Republic;

s.d. — a stone dust barrier;

rectilinear — means that the tests were carried out in the rectilinear 400 m gallery;

single bend — means that the tests were carried out with the barrier placed beyond a single unidirectional bend of the gallery;

double bend — means that the tests were carried out with barriers placed beyond two gallery bends, the second bend having been a two-directional one;

t_p — the time of putting the barrier into action or the time of the bag being torn;

Q_{II} — the quantity of water or of stone dust sufficient to stop the explosion;

= — means that the barriers were found to be equally effective;

pl — means that, though the Q_{II} contents were equal, yet the given type of the barrier stopped the explosion within a shorter distance — that is, that during the operation of stopping the explosion the distance covered by the flame beyond the zone of the barriers had been shorter;

a figure with the symbol of multiplication, e.g., "2.5 × " — means that for stopping an explosion by the given type of the barrier so many times less of stone dust than of water, or vice versa, had been sufficient;

? — means that it was impossible to compare the effectiveness of the barrier either on account of the absence of comparable values, or on account of the insufficient number of experiments;

The flame velocity values given in the table refer to the velocities prior to the flame's arrival to the barrier.

be stated that the distance of the barrier from the face of the parallel gallery was the same as its distance from the face of the rectilinear gallery because the distances of the two faces from the place at which the crosscut enters the 400 m gallery were equal. The results of the tests demonstrated that, in order to stop an explosion, the barriers placed close to the bend have to be somewhat heavier than the barriers placed at the same distance from the gallery's face in the tests carried out in a rectilinear gallery. The difference between the loads of stone dust amounts to about 50 kg/sq m.

The course of explosions is characterized by the following data: in the parallel gallery the velocity of the flame oscillated from 23 to 44 m/sec; in the crosscut from 44 to 109 m/sec, the mean velocity amounting to 75 m/sec. The velocity of the flame in the 400 m gallery — over the section up to 60 m in the direction of the gallery's outlet — oscillated between 102 and 549 m/sec the mean velocity amounting to 240 m/sec. The velocity of the flame before it reached the barriers oscillated between 100 and 230 m/sec the mean velocity being equal to 160 m/sec. Coal dust had been spread right from the face of the 400 m gallery so that the explosion, having entered this gallery from the crosscut, developed in two directions. The flame did not always reach the face of the 400 m gallery.

Figure 9.20 shows, by way of an example, the stopping of explosion No. 88 in the conditions described. In this figure one can see the bifurcation of the curve at the place at which the explosion enters the 400 m gallery from the crosscut and from which it develops in two directions. To facilitate the orientation in the data shown in the diagram the flame velocity curves were plotted according to detonator registration only.

The stopping of violent explosions started with the strong explosion initiator 30mPII. In these tests the *d*85 coal dust was used in which the content $n = 50$ percent. The results of the tests are presented in a graphic form in Fig. 9.21 showing two curves of the effectiveness of barriers, namely:

curve *1* — of the effectiveness of barriers in a rectilinear gallery,

curve *2* — of the effectiveness of barriers beyond two bends.

In both cases the dust and initiator used were identical. It follows from the comparison of the two curves that, up to a distance of about 60 m from the bend, the barriers in order to be able to stop explosions must be somewhat heavier than the analogous barriers in a rectilinear gallery. Beyond the distance of 60 m from the bend, the bend no longer influences the effectiveness of the barrier: the curves *1* and *2* merge into a single curve. After entering the 200 m gallery the explosion developed in two directions; yet it did not always reach the face of the 400 m gallery. In the parallel gallery the velocity of the flame oscillated from 12 to

38 m/sec the mean velocity amounting to 22 m/sec; in the crosscut it oscillated between 73 and 225 m/sec the mean velocity being equal to 115 m/sec.

Flame velocities just before reaching the barrier oscillated from 120 to 330 m/sec depending on the distance of the barrier from the place at which the explosion had been initiated; the mean velocity amounted to 170 m/sec. The times of putting the barriers into action t_p oscillated from 0 to 0.32 sec the mean value of t_p amounting to 0.18 sec. Analogously the mean values of t_p in the rectilinear gallery amounted to 0.22 sec. The difference, therefore, is immaterial. The graph of explosion No. 117 in Fig. 6.11*a* presents one of the results of this series. The barriers Q = = 75 kg/sq m placed at the distance of 100 m from the gallery's face stopped the explosion almost on the spot.

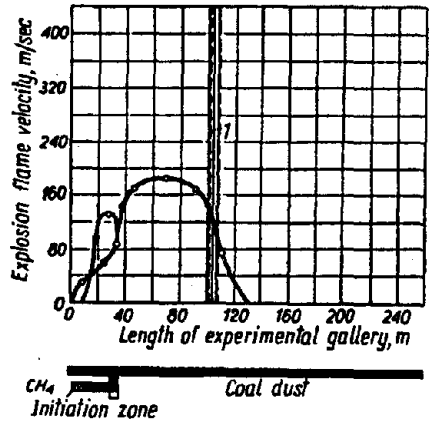


Fig. 9.20

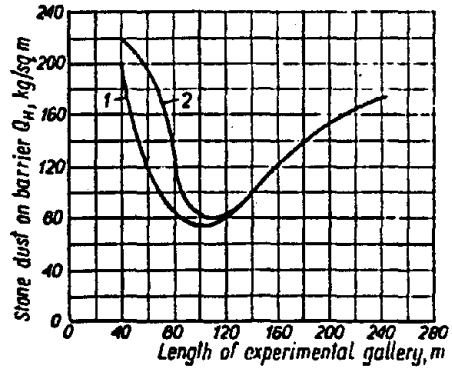


Fig. 9.21

Fig. 9.20. A diagram of explosion No. 88 of the d85 coal dust, n = 67.5%, initiator 30mPII; *1* — the barrier of 3 shelves, 337.5 kg of stone dust, Q = 45 kg/sq m stopped the explosion almost on the spot.

Fig. 9.21. A diagram of the effectiveness of stone dust barriers beyond the double and two-directional bend of the gallery in comparison with the effectiveness of barriers in a rectilinear gallery: coal dust d85, n = 50%, initiator 30mPII; *1* — the effectiveness of barriers in the rectilinear gallery; *2* — the effectiveness of barriers beyond the bends of galleries.

The stopping of relatively mild explosions started with a weak explosion initiator 4mPII. In these tests the natural d25 coal dust was used its content n = 20 percent. It has been demonstrated in the course of these tests that, in the conditions described, the effectiveness of barriers placed beyond the bends of galleries does not differ materially from the effectiveness of barriers in the rectilinear gallery.

Flame velocities before reaching the barrier oscillated from 40 to 200 m/sec the mean velocity being equal to 80 m/sec. In the parallel

gallery the velocity of the flame oscillated between 10 and 90 m/sec the mean velocity amounting to 27 m/sec; in the crosscut it oscillated from 33 to 75 m/sec the mean velocity being equal to 48 m/sec. The times of putting the shelves into action t_p just beyond the bend were comprised within the limits 0.04 and 2.8 sec. Large differences between the values of t_p were recorded depending on the distance of the shelves from the crosscut. The explosions progressed in a mild manner in spite of the fact that pure coal dust had been used in these tests. Of course, if the barriers were not employed the explosions would have developed into violent ones.

As an example showing the difficulty of stopping explosions at the short distance of 40 m from the gallery's face in Fig. 9.22 a diagram is given of explosion No. 149 not stopped by a barrier with $Q = 110$ kg/sq m. It is a characteristic feature of this explosion that, since it progressed in a very mild manner, the storied protecting barrier $Q = 45$ kg/sq m could not stop it either.

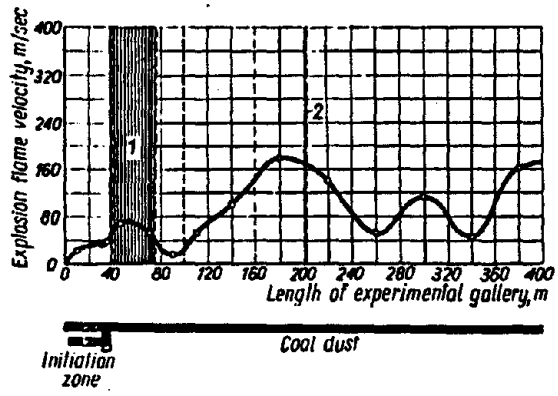


Fig. 9.22. A diagram of explosion No. 149 of the $d25$ natural coal dust, $n = 20\%$, initiator 4mPII; *1* — the barrier of 15 shelves, 825 kg of stone dust, $Q = 110$ kg/sq m did not stop this explosion; *2* — storied protecting barrier, 1 × 3, 337.5 kg of stone dust, $Q = 45$ kg/sq m.

The stopping of violent explosions started with a strong explosion initiator 50 cu m CH_4. In these tests the natural $d25$ coal dust was used its content $n = 20$ percent. The flame velocity just before the barriers, depending on the position of the barriers, oscillated from 100 to 570 m/sec the mean velocity amounting to 350 m/sec. It has been established that, under described conditions, already at the distance of the barrier amounting to 100 m from the gallery's face — that is, 60 m beyond the gallery's bend, a much larger quantity of stone dust (240 kg/sq m) had been required in order to stop the explosion than would have sufficed in a rectilinear gallery.

A diagram of explosion No. 497 shown in Fig. 6.11b presents one of the results of the tests of this series. The barrier $Q = 240$ kg/sq m, situated at the distance of 100 m from the face of the gallery, stopped this explosion within a short distance beyond the barrier.

A recapitulation of the results of investigations on the effectiveness of stone dust barriers beyond two bends of galleries of the same cross section area. It has been found that bends of galleries affected variously the degree of the effectiveness of barriers according to the different types of explosions. Bends did lower the degree of the effectiveness of barriers — whether placed just beyond them or at a longer distance from them — depending on the kind of the initiator used and on the development of the coal dust explosion. The process of stopping explosions with barriers beyond the bends of galleries is more complicated than the same process in rectilinear galleries.

A stress should be laid on the fact, however, that in all cases in which bends were found to exert an influence on the effectiveness of barriers the quantities of stone dust sufficient to stop explosions were still considerably smaller than those required by regulations for methane seams and, in the majority of cases, smaller also than the quantities prescribed by regulations for nonmethane seams.

It has been established that stone dusting of the zone just beyond a bend, even over a relatively small length, for example, about 60 m, greatly facilitates the stopping of an explosion. Particularly the dusting with stone dust of the zone in which the barrier is situated raises considerably the barrier's effectiveness and provides this effectiveness with a very considerable safety factor. When barriers are placed close to gallery bends it is recommended to use shelves 35 cm broad since they are more easily put into action which is important, since the explosion blast frequently weakens after passing through gallery bends.

9.1.11.3. Investigations on the effectiveness of barriers of the *EM Barbara* type placed beyond gallery bends in the cases in which the cross sectional area of a gallery is reduced at this gallery's point of junction with the gallery beyond the bend. In mines gallery workings of different cross sectional areas are frequently joined together; on account of this it was deemed necessary to carry out the tests of barriers under such conditions.

Explosions were initiated in the connecting crosscut at the distance of about 120 m from the 400 m experimental gallery. The cross sectional area of the connecting crosscut amounts to 5 sq m; that of experimental gallery — 7.5 sq m. At the point where the crosscut joins the experimental gallery there is a narrowing in the form of the double timber the cross sectional area of which measures 1.4 sq m. The examined explosions

progressed in a very characteristic manner. The explosion flame velocity in the connecting gallery has been practically regular and amounted to about 80 m/sec. After the passing of the explosion to the 400 m experimental gallery a very sudden acceleration of the flame's velocity was observed sometimes up to about 1000 m/sec and that within a small distance beyond the bend. Such progress of the explosion has had a very marked influence on the effectiveness of the barriers placed in the experimental gallery. Stone dust barriers had been placed just beyond the bend at the distance of about 3 m from the gallery's face and at the distances of 20, 40, 60, 100, 140 and 160 m from the bend.

9.1.11.4. Stopping violent explosion with barriers placed in the 400 m experimental gallery beyond the single bend of the gallery. In these tests the *d*85 coal dust was used the content *n* of which was equal to 50 percent. A weak explosion in the connecting gallery served as the initiator. Dispersion conditions were the easiest.

The flame velocity before the barriers placed in the 400 m gallery oscillated between 100 and 1200 m/sec depending on the distance of the barrier from the place at which the galleries meet. The mean velocity amounted to 440 m/sec.

The results of the tests are given in a graphic form in Fig. 9.23 which shows two curves of the effectiveness of barriers, namely:

curve *1* —the effectiveness of barriers in a rectilinear gallery corresponding to that shown in Fig. 9.12 obtained under the same dust conditions but with the use of the strong explosion initiator (30mPII),

curve *2* — the effectiveness of barriers placed beyond a bend.

A comparison of the curves *1* and *2* shows that there is a tremendous difference between the effectiveness of barriers in these conditions. The

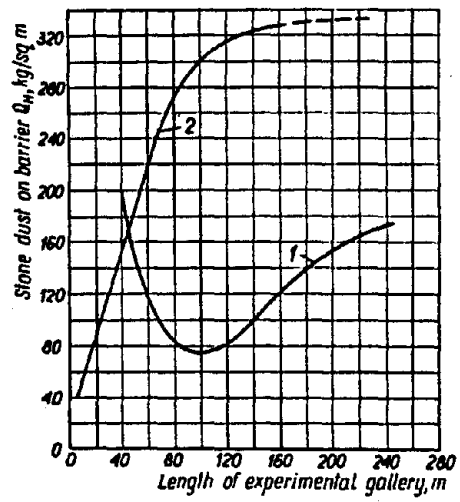


Fig. 9.23. A diagram of the effectiveness of stone dust barriers placed beyond a unidirectional bend of galleries, with different cross sectional areas, in comparison with the effectiveness of barriers in a rectilinear gallery: the *d*85 coal dust, $n = 50\%$, initiator 10mPII, a mild explosion in the connecting gallery; *1* — the effectiveness of barriers in a rectilinear gallery; *2* — the effectiveness of barriers beyond the bend.

stopping of an explosion just beyond the bend is very easy. A barrier with $Q = 33.6$ kg/sq m will serve this purpose quite well.

At the distance of 40 m beyond the bend, explosions have been stopped with even lighter barriers than those used in the rectilinear gallery.

With the increase of the barrier's distance from the bend, in the proximity of the 60th m, the magnitude of the barrier capable of stopping an explosion grows very materially. The velocity of the flame before it reaches the barrier is very high and the explosions at this distance from the bend become very violent. As an illustration of the results of the tests described here a diagram is given in Fig. 9.24 of explosion No. 485 which could not be stopped by the barrier $Q = 250$ kg/sq m placed 100 m beyond the bend — that is, 220 m from the place at which the explosion has been initiated. It was ultimately stopped in the protecting zone with pure stone dust.

As one can see in Fig. 9.24 the registrations of the flame's velocity done by two methods produced greatly differing results; in any case the velocity of the flame before the barrier amounted to about 1000 m/sec. The times of putting shelves into action t_p oscillated between -0.39 and 3.96 sec. The extreme values of t_p, however, were seldom recorded. A neg-

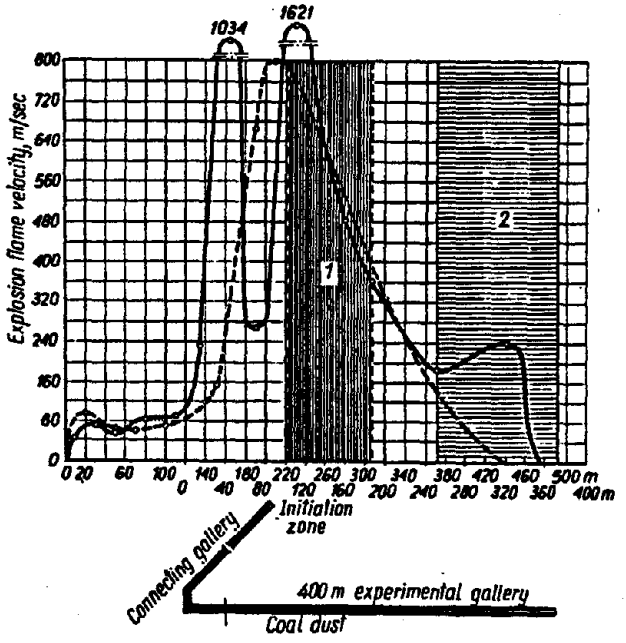


Fig. 9.24. A diagram of explosion No. 485 of the d85 coal dust, $n = 50\%$, initiator — a mild explosion in the connecting gallery; *1* — the barrier of 30 shelves, 1875 kg of stone dust, $Q = 250$ kg/sq m did not stop this explosion; *2* — protecting zone, 2478 kg of stone dust, $Q = 330.5$ kg/sq m.

ative value of t_p has been established in only one case. After the exclusion of extreme values of t_p its mean walue amounted to 0.4 sec.

Under the conditions discussed here the stopping of explosions had been very easy with barriers placed just beyond the bend (where the two galleries join); at the distance of 400 m from the bend the stopping of explosions continued to be easier than in a rectilinear gallery the quantity of stone dust on the barrier, sufficient to stop an explosion at this distance from the bend, amounting to only 60 percent of the corresponding quantity required in a rectilinear gallery. But then, at the distance of 100 m from the place where the galleries join, the difficulty of stopping explosions grew so much that the barrier capable of stopping the explosion had to carry 4.3 times as much of stone dust as a barrier situated in analogous conditions of dustiness in a rectilinear gallery.

9.1.11.5. Stopping very violent explosions with barriers placed in the 400 m experimental gallery beyond the single bend of the gallery. In these tests the natural $d25$ coal dust was used the content n of which amounted to 20 percent. A weak explosion in the connecting gallery served as the initiator. The easiest dispersion conditions were procured.

The results of the tests are presented in the form of graphs in Fig. 9.25 which shows two curves of the effectiveness of barriers:

curve *1* — of the effectiveness of barriers in a rectilinear gallery; it corresponds to the curve *2* in Fig. 9.14,

curve *2* — of the effectiveness of barriers in the conditions described here placed beyond the galleries' bend.

As can be seen in Fig. 9.25 the influence of the bend upon the effectiveness of barriers has been still greater here than in the case presented in Fig. 9.23. This is due to the higher violence of explosions. The flame's velocity in the 400 m gallery grew distinctly with the distance from the bend. This velocity grew from 60 m/sec just beyond the bend to the maximum value of 1400 m/sec found at the distance of 80 m from the bend. The mean velocity of the flame in these experiments amounted to 850 m/sec. The mean velocity is merely a value characterizing the conditions of the tests in a very general maner only, since the velocities of the flame, as has been demonstrated in all relevant experiments, very distinctly depended upon the distance from the bend. In separate experiments great oscillations of flame velocities were recorded the distance from the bend being the same. The course of explosions in the connecting gallery was quite analogous to that observed in the former experimental series. But in the 400 m gallery explosions developed with a higher acceleration. It was easy to stop an explosion with barriers placed just beyond the bend as is shown in Fig. 9.25. With the increase of the barrier's distance from the bend the difficulty of stopping explosions grew very rapidly. At the

distance of 40 m, in order to stop an explosion assuredly, it was necessary to have $Q_{II} = 320$ kg/sq m; similarly at the distance of 80 m $Q_{II} = 340$ kg/sq m. As examples of the process of stopping explosions in these

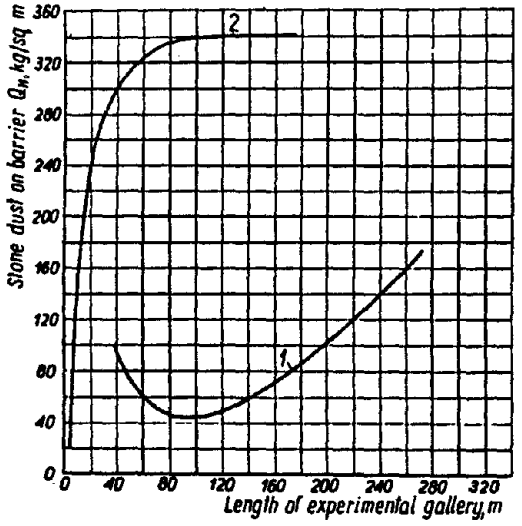


Fig. 9.25. A diagram of the effectiveness of stone dust barriers placed beyond a unidirectional bend of galleries of different cross sectional areas in comparison with the effectiveness of such barriers in a rectilinear gallery: the $d25$ natural coal dust, $n = 20\%$, initiator — a mild explosion in the connecting gallery; *1* — the effectiveness of barriers in a rectilinear gallery; *2* — the effectiveness of barriers beyond a bend.

conditions in Fig. 9.26*a* a diagram is given of explosion No. 481 which could not be stopped by the barrier $Q = 150$ kg/sq m placed at the distance of 80 m beyond the bend. This explosion was only stoped in the protecting zone.

In Fig. 9.26*b* a diagram is given of explosion No. 483 stopped by the barrier $Q = 300$ kg/sq m placed at the distance of 100 m from the bend.

The values of t_p oscillated from -0.12 to 1.18 sec. When the barriers had been placed just beyond the bend the values of t_p were always positive and oscillated between 1.4 and 1.18 sec. The negative values were recorded already at the distance of 20 m from the bend. In the presence of such violent explosions, in which a high acceleration of the flame's velocity had been observed immediately after passing through the bend, the quantities of stone dust on a barrier capable to stop these explosions were, already at the distance of 40 m from the bend, about 3.7 times as big as those required in a rectilinear gallery, and at the distance of 80 m from the bend — 6.5 times as big.

The ease with which such explosions can be stopped close to the bend

can be explained by the fact that in the vicinity of the bend the explosion just begins to develop. On the other hand the difficulty of stopping such explosions, at distances not exceeding two or three score of meters, is due to the high acceleration of the flame in consequence of which it achieves a very high velocity before reaching the barrier. Though many an explosion have been stopped with the value of t_p being close to zero or even negative the fact that the time is extremely short, during which the conditions have to be created either for stopping the explosion or for its propagation, is often responsible for the barrier failing to disperse adequately stone dust at the moment of the arrival to the barrier of the tongue of the flame, particularly if this arrival occurs with a high velocity.

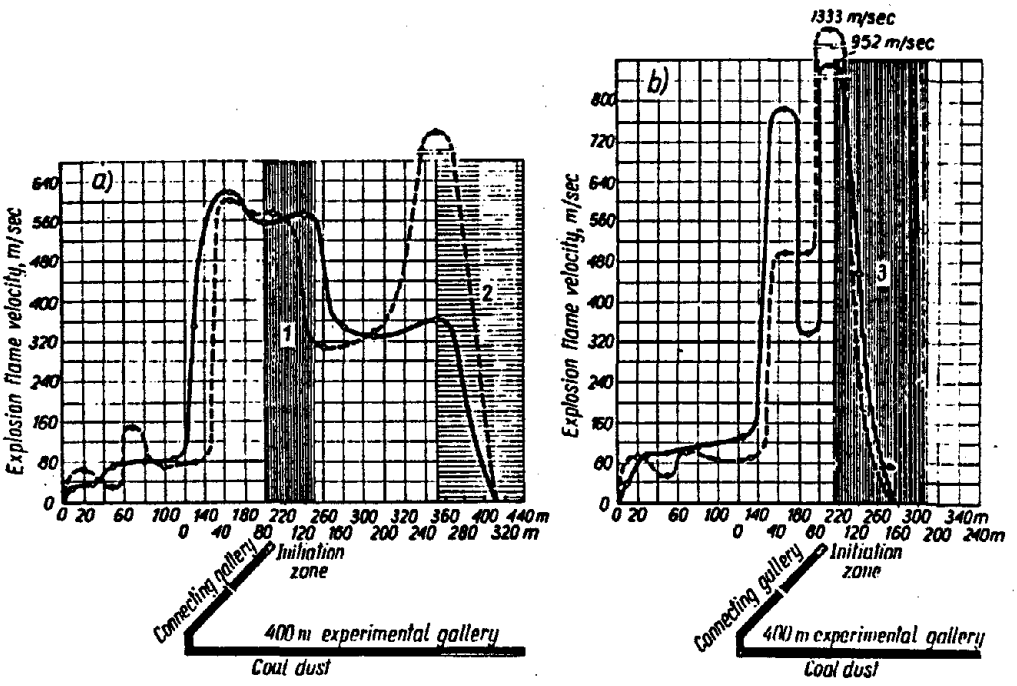


Fig. 9.26. Explosion diagrams: *a* — explosion No. 481 of the d25 natural coal dust, $n = 20\%$, initiator — a mild explosion in the connecting gallery; *1* — the barrier of 18 shelves, 1125 kg of stone dust, $Q = 150$ kg/cq m did not stop this explosion; *2* — protecting zone, 2478 kg of stone dust, $Q = 330$ kg/sq m; *b* — explosion No. 483 of the d25 natural coal dust, $n = 20\%$, initiator — a mild explosion in the connecting gallery; *3* — the barrier of 36 shelves, 2250 kg of stone dust, $Q = 300$ kg/sq m stopped this explosion.

How difficult it is to estimate the effectiveness of a barrier's action on the basis of the value of t_p is demonstrated by the pertinent values of t_p in the cases of the propagation or the stoppage of explosions.

In all cases in which explosions were propagated the time values

oscillated between −0.38 and 1.18 sec the mean value of t_p amounting to 0.05 sec.

The values of t_p for the cases in which explosions were stopped oscillated from −0.3 to 2.8 sec the mean value amounting to 0.35 sec.

On account of the very short time intervals observed in both cases it cannot be concluded that certain minimum values of t_p, necessary for the effective operation of barriers, play a decisive role in all these cases. Nevertheless it is a fact beyond dispute that, when a barrier is put into action so as to create an effective cloud of stone dust before the arrival of the flame, the explosion will be stopped assuredly. This has been confirmed by experiments carried out with triggered barriers from which stone dust is dispersed through the action of an explosive at the required period of time prior to the arrival of the flame.

9.1.11.6. Stopping very violent two-directional coal dust explosions with barriers of the *EM Barbara* type placed beyond bends of galleries. The development of two-directional explosions has been discussed in Section 6.7.3.2. The coal dust explosions in question have been initiated in a connecting gallery from which they developed entering both the 200 and the 400 m experimental galleries.

Taking account of the fact that, in mines, a coal dust explosion can easily develop in several directions simultaneously investigations were carried out in the *EM Barbara* on stopping very violent explosions developing in two directions and initiated in the connecting gallery (analogously to experiments discussed in Section 6.7.3.2).

Stone dust barriers in the 400 m gallery were placed at distances of from 80 to 170 m from the place at which explosions have been initiated. The volume concentration of stone dust $Q_v = 5.83$ kg/cu m; barriers were placed in the 200 m gallery at distances of from 80 to 150 m from the place at which explosions have been initiated. The volume concentration of stone dust $Q_v = 8.1$ kg/cu m.

The distances of the barriers from the respective points at which the connecting gallery joins the two experimental galleries were accordingly shorter by 80 m.

In all of the experiments the barriers have stopped the explosions in the 400 m gallery with quantities of stone dust Q amounting to from 105 to 180 kg/sq m. In the 200 m gallery, however, there has been recorded one propagation of an explosion with the quantity of stone dust $Q = 105$ kg/sq m. Unquestionably it can be maintained that, if the quantities of stone dust were increased so as to comply with regulation requirements — that is, to $Q = 400$ kg/sq m, the barriers in the 200 m gallery would have also stopped coal dust explosions even as violent as the ones which took

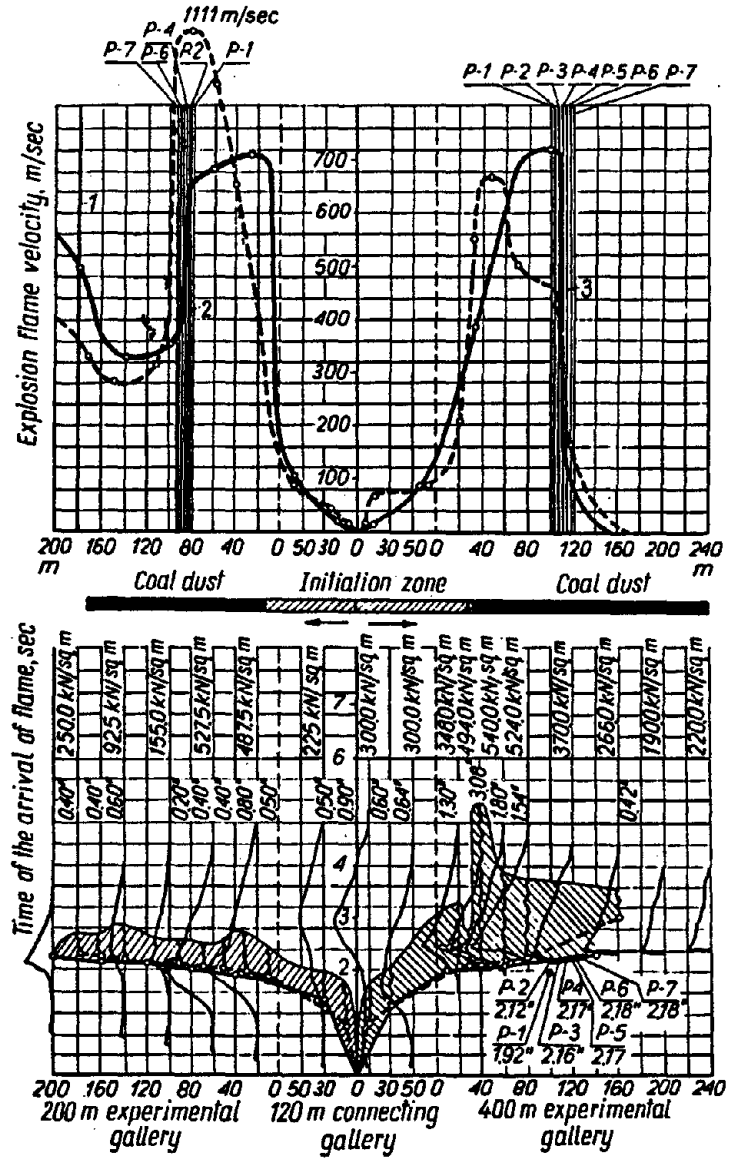


Fig. 9.27. A diagram of the two-directional explosion No. 902 of the d85 coal dust, $n = 60\%$, stopped by the stone dust barrier in the 400 m gallery and not stopped by the barrier in the 200 m gallery; *1* — protecting barrier, $Q = 45$ kg/sq m; *2* — stone dust barrier of 7 shelves at 2 m distances, 525 kg of stone dust, $Q = 105$ kg/sq m; *3* — stone dust barrier of 7 shelves at 3 m distances, 785.5 kg of stone dust, $Q = 105$ kg/sq m. Symbols as in Fig. 6.4.

place in the experiments discussed here. The velocity of the flame before the barrier in the 200 m gallery amounted to about 1000 m/sec.

The difference between the effectiveness of barriers in the 200 and the 400 m galleries might have been only an apparent one since, naturally, the process of stopping explosions in the 200 m gallery could be observed over a shorter stretch than in the 400 m gallery.

In order to illustrate these interesting experiments in Fig. 9.27 a diagram is given of the two-directional explosion No. 902 stopped in the 400 m gallery but not stopped on the spot in the 200 m gallery.

9.1.11.7. Practical conclusions from the investigations concerning the effectiveness of barriers beyond bends in galleries. In order to have explosions stopped assuredly one should aim at placing stone dust barriers in rectilinear workings in which there is a likelihood of explosions being initiated. If this should happen to be impossible, as far as the whole barrier is concerned, at least a part of it ought to be placed in such a gallery and the remaining part as close beyond the bend as possible; or, when there is no room for such an arrangement, the whole barrier could be placed close beyond the bend. If it were impossible to do this then — at any rate — the distance between the barrier and the gallery's bend should be small and a great care should be taken to have the zone close to the bend dusted with stone dust. In the course of the experiments it has been found that the dusting with stone dust of even a short zone of 30 m, in which the content of n had been raised through this action to 80 percent, resulted in the stopping within this zone of very violent explosions discussed in Section 9.1.11.5. However, to make such zones properly effective under the operational conditions in mines they ought to be at least 200 m long. The most effective is the location of the barrier in a zone carefully stone dusted with $n = 85$ percent. Stone dust barriers so placed, complying in other respects with regulation requirements, will stop all kinds of coal dust explosions from very weak to exceptionally violent ones the velocities of which approach 1000 m/sec. The depth of the barrier's frame should be at least 20 cm but, wherever the dimensions of the working will permit, it should even be 30 cm for, as had been demonstrated in the course of the investigations, this has a very positive effect on the growth of the time of putting the barrier into action t_p.

9.1.11.8. The influence of the time t_p in which barriers are put into action on their effectiveness. In the investigations on the effectiveness of barriers, discussed in several foregoing sections, the times of putting barriers into action were short. Only exceptionally values of t_p were obtained above 3 sec; as a rule these values did not exceed 2 sec.

In the conditions of a rectilinear gallery stone dust barriers have been very effective with low values of t_p seldom exceeding 1 sec and frequently approaching zero. Conditions under which investigations were carried out had been limited by the characteristics of available workings and by the

maximum distance of the barrier from the place at which explosions could be initiated amounting to 400 m. In the mining practice the distance of the barrier from the place of the initiation of explosions can be much longer than that. Besides, the course of the explosion can be much more complicated than it actually was in the conditions in which experiments were made. Consequently the time in which the barrier is put into action t_p can be much longer in practice than that established in the course of experiments. It ought to be mentioned that in practice there are cases in which the main barrier is placed as far as 2000 m from the place of a likely initiation of an explosion. In view of such facts it was necessary to investigate the influence of higher values of t_p on the effectiveness of barriers.

The investigations in question [53] were carried out in the following manner: the barrier (consisting of 35 cm shelves) was placed at the distance of 100 m from the faces: of the 400 m gallery, and of the parallel gallery in which the explosion of 50 cu m CH_4 has been initiated by firing a charge of 750 g of gunpowder. This explosion caused the barrier to be put into action. After a certain prearranged time interval a violent coal dust explosion was initiated at the 400 m gallery with the 30mPII initiator; in this explosion the d85 coal dust was used its $n = 50$ percent. The mean flame velocity before the barrier amounted to 345 ± 30 m/sec. In these conditions the value of t_p varied within the limits of from 0.43 to 5.6 sec. In this way the minimum quantities of stone dust Q_{II} (kg/sq m) were found sufficing to stop explosions depending on the value of t_p.

The results of these investigations are given in the form of graphs in Fig. 9.28a. The plotted solid line *3* corresponds directly to the arrangement of dots representing the results of experiments. Apart from that, by employing the method of the discriminant analysis, a dotted straight line *1* has been found delimiting the extreme values of parameters in the cases in which, in the course of experiments, explosions were propagated. Equation of the straight line *1* has the following form

$$t_p = 0.0276Q - 1.32 \tag{9.1}$$

The parallel straight line *2* is a line representing the probability of the propagation of an explosion across the barrier — at the relevant parameters t_p and Q — to be equal to 2.5 percent. Equation of the straight line *2* has the following form

$$t_p = 0.0276Q - 1.56 \tag{9.2}$$

In the course of these experiments it has been found that for the values of t_p up to about 1 sec the minimum load of stone dust on a barrier, $Q_{II} = 45$ kg/sq m, was sufficient. With the growth of the value of t_p the value of Q_{II} rose to the magnitude of $Q_{II\,max} = 150$ kg/sq m.

It is a particularly distinctive trait of these experiments that, beginning with the value of t_p equal to about 2.8 sec according to the straight line *1* or to about 2 sec according to the straight line *2*, the value of Q_{II} ceased to be dependent on the further growth of the value of t_p within the limits of t_p values employed in the experiments.

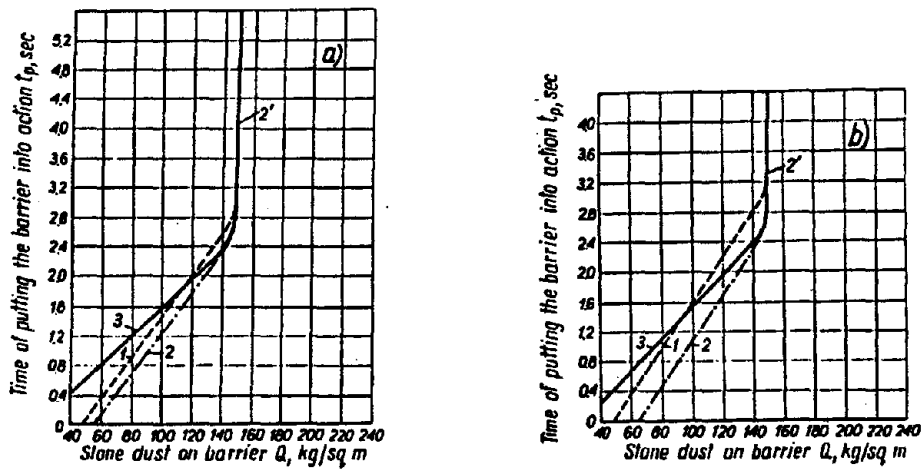


Fig. 9.28. A diagram of the effectiveness of stone dust barriers depending on the time of putting the barrier into action t_p; *a* — refers to 35 cm shelves: d85 coal dust, n = 50%, initiator 30mPII; *b* — refers to 50 cm shelves: d85 coal dust, n = 50%, initiator 30mPII.

Quite analogous experiments were made with the use of stone dust barriers composed of 50 cm shelves. The values of t_p were made to vary from 0.06 to 6.32 sec. The mean flame velocity before the barrier amounted in this series of experiments to 255±30 m/sec. The results of the experiments are shown in the form of graphs in Fig. 9.28*b*. Straight lines *1* and *2* were delineated and their equations found analogously to those found in reference to Fig. 9.28*a*.

Equation of the line *1*

$$t_p = 0.03066Q - 1.48 \tag{9.3}$$

Equation of the line *2*

$$t_p = 0.03066Q - 2.02 \tag{9.4}$$

The solid line *3* and *2'* represents the curve plotted on the basis of the direct arrangement of the dots representing the results of experiments.

The results of the tests demonstrated that for the values of t_p below 1 sec the value of Q_{II} amounted to 75 kg/sq m. However, the $Q_{II\,max}$ was the same as that in the case of the 35 cm shelves and amounted to

150 kg/sq m. In this series of experiments the value of Q_{II} became firmly fixed above the value of $t_p = 3.1$ sec.

The stability of the effectiveness of barriers above a certain value of t_p can be explained as follows: if the value of t_p is sufficiently high at the time when the flame reaches the barrier most of the stone dust, which has previously been thrown off the barrier, no longer forms a part of the dust cloud in the air but has settled already on the floor and on the walls of

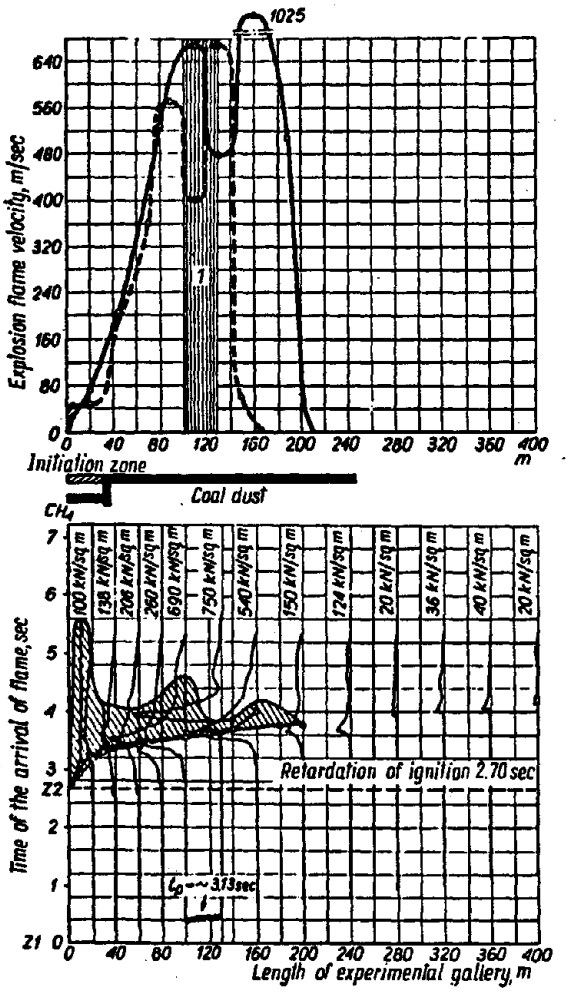


Fig. 9.29. A diagram of the explosion No. 434 of the d85 coal dust, $n = 50\%$; initiator 30mPII in the 400 m gallery; initiator used for putting the barriers into action — 50 cu m CH_4 in the parallel gallery; *1* — stone dust barrier of 10 shelves, 1125 kg of stone dust, Q = 150 kg/sq m stopped the coal dust explosion 80 m beyond the barrier with $t_p = 3.13$ sec. Z.2 — means initiator 2 — i.e., initiation of explosion by 30mPII; Z.*1* — means initiator 1 — i.e., initiation of explosion by 50 cu m CH_4.

the gallery creating in fact, as it were, a freshly dusted zone. The effectiveness of this zone is bound up with the secondary raising of the dust into the air.

As one of the examples illustrating this series of experiments Fig. 9.29 presents a diagram (of explosion No. 434 stopped by the barrier $Q = 150$ kg/sq m with $t_p = 3.13$ sec at the distance of 80 m beyond the barrier. This diagram is very interesting because the flame, before reaching the barrier, acquired the velocity of about 1000 m/sec and, in spite of this, it has been stopped. The diagram shows that there were certain differences between the detonator and the photoelectric registrations.

9.1.12. The effectiveness of barriers depending on the conditions of stone dust dispersion in the cross section of the gallery

9.1.12.1. General information. All tests of stone dust barriers discussed so far had been carried through with barriers of the length required by regulations and the barriers has been placed under the roof also according to regulations. Thus we have dealt with ordinary stone dust barriers.

As it has been explained in the beginning of the chapter on barriers their effectiveness depends upon the equal dispersion of stone dust in the cross section of the working, upon the length of the cloud and upon the content in it of incombustible matter.

In order to investigate various conditions of the dispersion of stone dust a fundamental research work has been done in the *EM Barbara* the results of which are very concisely described in this section [54].

Three magnitudes have to be considered which concern the quantities of coal dust and its distribution on a barrier:

Q — the quantity of stone dust on the whole barrier per 1 sq m of the gallery's cross section; this magnitude is set forth normally by regulation requirements, kg/sq m;

Q_1 — the quantity of stone dust on single shelf per 1 sq m of the gallery's cros section, kg/sq m;

Q_v — the concentration of stone dust in the zone in which the barrier is situated — that is, the proportion of the quantity of stone dust on the whole barrier to the volume of the section of the working occupied by the barrier, kg/cu m.

When the effectiveness of barriers had been discussed in previous sections this effectiveness was expressed by the magnitude Q_{II} sufficient to stop a coal dust explosion in given conditions. Unquestionably for fundamental, as well as practical, considerations it is desirable to know the minimum value of Q_1 and the minimum value of Q_v which still would make a barrier operate effectively.

Thus the purpose of the investigations had been to find how a reduction of the concentration of a stone dust cloud influences the effectiveness of barriers. It should be explained that the value of Q_v can be changed by changing the value of Q_1 and by changing the distance between the shelves. Besides, it is very important to determine the effectiveness of the lateral dispersion of stone dust — that is, its dispersion in the space between the shelf and the gallery sidewalls. Of a considerable importance also is the examination of the effectiveness of the dispersion of stone dust "upward" in other words, the examination of the influence of the lowering of the shelves upon their effectiveness.

The tests in question were carried out in the rectilinear 400 m experimental gallery the cross sectional area of which amounts to 7.5 sq m; in the rectilinear 200 m experimental gallery of the cross sectional area equal to 5 sq m, and in the connected galleries.

9.1.12.2. The results of investigations on the effectiveness of stone dust barriers depending on the values of Q_1 and Q_v when the shelves are placed symmetrically. In the tests described in preceding sections the values of Q_1 for the barriers of the *EM Barbara* type, in both experimental galleries, amounted to:

— in the 200 m gallery for shelves:

240 × 50 cm	$Q_1 = 22.8$ kg/sq m
240 × 50 cm	$Q_1 = 15.0$ kg/sq m
240 × 35 cm	$Q_1 = 12.5$ kg/sq m
200 × 35 cm	$Q_1 = 12.5$ kg/sq m

— in the 400 m gallery for shelves:

250 × 50 cm	$Q_1 = 15.0$ kg/sq m
250 × 35 cm	$Q_1 = 8.33$ kg/sq m

In the tests, the results of which are discussed in this section, the separate loads of stone dust on shelves oscillated from 15 to 112.5 kg. The values of Q_1 oscillated from 2.06 to 15 kg/sq m. The values of Q_v were changed within the limits of from 7.5 to 0.17 kg/cu m.

The shelves were placed symmetrically in the experimental galleries (Fig. 9.30).

The tests were carried out at different distances between the barriers and the face of the gallery usually at distances of 60, 100 and 200 m. The conditions of coal dust explosions varied in correspondence to the diagrams shown in Figs. 9.12, 9.14 and 9.16. In many tests the conditions were made more difficult by the presence of the d85 coal dust before the barrier, in the zone of the barrier, and 20 m beyond the barrier. The easiest dispersion conditions were procured for these tests.

Mild, as well as very violent, explosions were included in the in-

vestigations. The summary of the results of these investigations presented here, therefore, is valid for the above wide range of various explosions.

Reducing the length of the shelves to 50 cm it has been found that barriers of the *EM Barbara* type effectively stop coal dust explosions with quantities of stone dust on the barriers Q smaller than those required by regulations, provided that the following conditions are satisfied:

— the value of Q_v should not be lower than 0.5 kg/cu m,

— the value of Q_1 should not be lower than 5 kg/sq m.

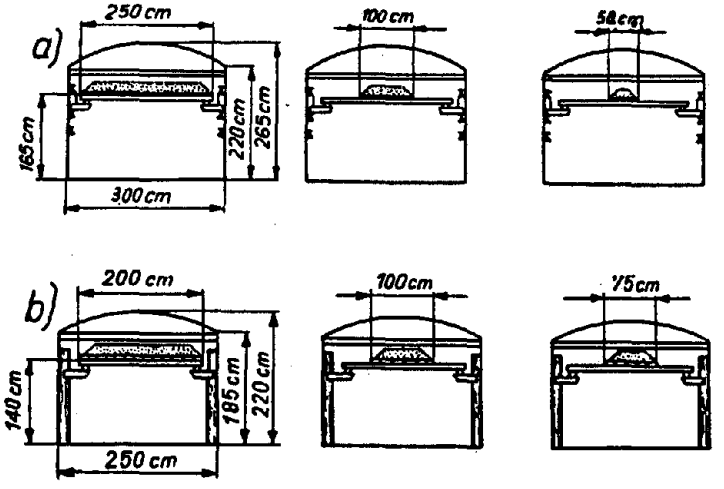


Fig. 9.30. The position of shelves in the gallery: *a* — shelves placed symmetrically in the 400 m experimental gallery; *b* — shelves placed symmetrically in the 200 m experimental gallery.

Using shelves of the normal length and increasing merely the distances between them it was found that barriers can act effectively also with shelves distributed at longer distances from each other on the condition analogous to the one given above, namely, that the value of Q_v should not be lower than 0.5 kg/cu m. The identity of this condition with that mentioned in reference to shortened shelves is noteworthy.

It would be proper to mention that in many cases coal dust explosions have been stopped with barriers in which the distances between the shelves were large and the value of Q_v amounted to about 0.25 kg/cu m or even less.

9.1.12.3. Distributed barriers. For any particular spacing between the shelves there is a certain appropriate number of shelves sufficient to stop a given kind of a coal dust explosion provided that the distance between the shelves does not exceed the maximum distance at which the barrier is still capable of stopping the explosion. If the distance between the

shelves should exceed this maximum magnitude no increase in the number of shelves could result in stopping an explosion.

In the experiments discussed here the courses of the explosions have been very characteristic. The shelves consecutively abated the explosion ultimately causing the fading of the flame.

When the distance between shelves is too large the explosion — having weakened through the action of one shelf — has the possibility of developing again and of achieving an acceleration of the flame's velocity. In the end the explosion can pass through all shelves no matter how numerous they are.

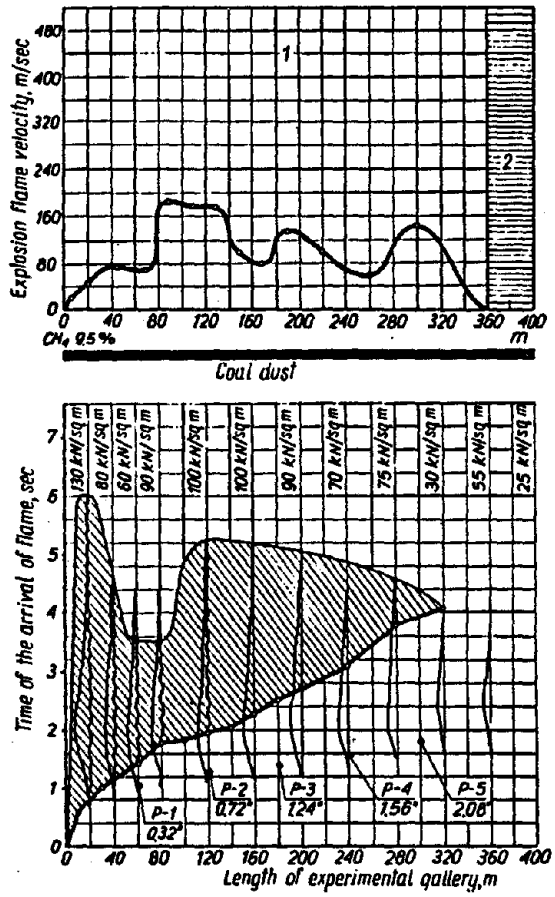


Fig. 9.31. A diagram of explosion No. 1015 of the natural d25 coal dust, $n = 17.1\%$, initiator — 50 cu m CH_4 (9.5%); electrical detonator aplied to the paper partition; *1* — a stone dust (distributed type) barrier of 5 shelves, 562 kg of stone dust, $Q = 75$ kg/sq m stopped this explosion; *2* — protecting zone, 826 kg of stone dust, $Q = 75$ kg/sq m. Symbols as in Fig. 6.4.

As an illustration of the above very interesting investigations a diagram of explosion No. 1015 is given in Fig. 9.31 of the natural d25 coal dust, $n = 17.1$ percent; initiator 50 cu m CH_4; ignition with an electric detonator close to the paper partition. The stone dust barriers employed in this case, $Q = 75$ kg/sq m, consisted of five shelves 250 cm long and 50 cm broad the spacing between the shelves being equal to 60 cm; $Q_v = 0.31$ kg/cu m.

This explosion is quite characteristic on account of its course being close to the limit parameters. Though the explosion flame did pass through all the shelves, yet it could not gain any acceleration and, essentially, it can be regarded as stopped. Noteworthy is the increase of the value of t_p with the growth of the distance of the shelves from the gallery's face. Such an increase of the t_p values may be considered to be rather harmful to the action of the shelves. However, in the cases of violent explosions the reduction of the values of t_p might have the effect of creating optimal conditions for the effectiveness of the separate shelves.

Investigations described in Section 9.1.12.2 led to the formulation of concrete practical conclusions concerning the possible use of what are called distributed barriers. The purpose of the use of distributed barriers is to supply a substitute for the dusting of workings with stone dust, particularly whenever the dusting with stone dust could be either ineffective or extremely difficult to execute under the operational conditions in mines.

Distributed barriers are barriers in which the shelves are placed at such distances from each other that permit of satisfying the following basic conditions: Q_v should not amount to less than 1 kg/cu m. The value of Q_1 should not be lower than 0.5 kg/sq m. Although it has been stated in the preceding section that to assure an adequate effectiveness of the barriers of this type it is sufficient to satisfy the condition of having Q_v not lower than 0.5 kg/cu m or even $Q_v = 0.25$ kg/cu m — yet, for the purpose of attaining to an appropriate level of confidence the above higher requirements should be complied with.

The distributed barriers, called also continuous barriers, represent a considerable practical simplification in comparison with the dusting of workings with stone dust. Wherever coal dust in workings is produced intensively stone dusting has to be supplemented frequently. The distributed barriers, on the other hand, remain effective as long as the stone dust on these barriers retains the proper dispersibility. The barrier of this type stop explosions at various distances from the first shelf. It would have been very useful to effect the stoppage within the shortest possible stretch of the working but this depends on the way in which the explosion develops. Each shelf influences the development of the explosion and changes the conditions in which the next shelf will act. Thus there is

always a chance that one of the shelves will disperse stone dust in the most favorable conditions.

It ought to be strongly emphasized that in no circumstances the distributed barriers can be regarded as substitutes for ordinary barriers. The latter are used to stop explosions at the place in which the barrier is situated or within only a small distance beyond the barrier. When the distributed barriers are used there is obviously a considerably greater probability that ultimately a coal dust explosion will be stopped, yet the distance covered by the explosion will be longer. It should be remembered that the longer is the distance covered by the flame the greater are the consequences of the explosion in the first place on account of the larger quantities of the carbon monoxide produced and also on account of the fact that there is more danger of men suffering burns or being injured by the blast.

In Fig. 9.32 a diagram is given of explosion No. 1042 stopped with distributed barriers in which, however, the flame covered the distance of about 300 m. In this case the distances between the shelves amounting to 35 m were by far too long since the value of Q_v for this barrier was equal to 0.278 kg/cu m.

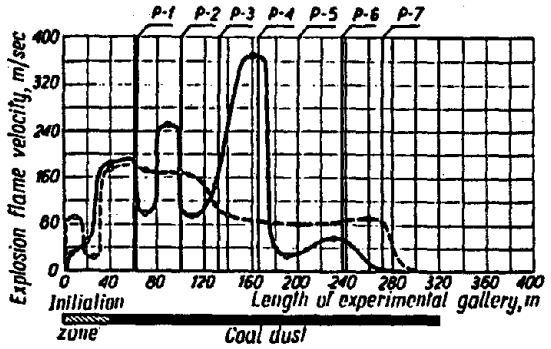


Fig. 9.32. A diagram of explosion No. 1042 of the d85 coal dust, $n = 50\%$, initiator 40mPII, $Q_v = 0.278$ kg/cu m; the barrier stopped this explosion; distance between the 35 cm shelves amounted to 35 m. Symbols as in Fig. 6.4.

If in the case of this explosion the condition that Q_v should be equal to 1 kg/cu m were satisfied the range of the flame, unquestionably, would have been considerably smaller.

The effectiveness of distributed barriers has also been tested under conditions of a two-directional development of explosions [60]; the results obtained were analogous to those obtained for unidirectional explosions.

In Fig. 9.33 a diagram is given by way of an example of the stopping of the two-directional explosion No. 1150 with distributed stone dust

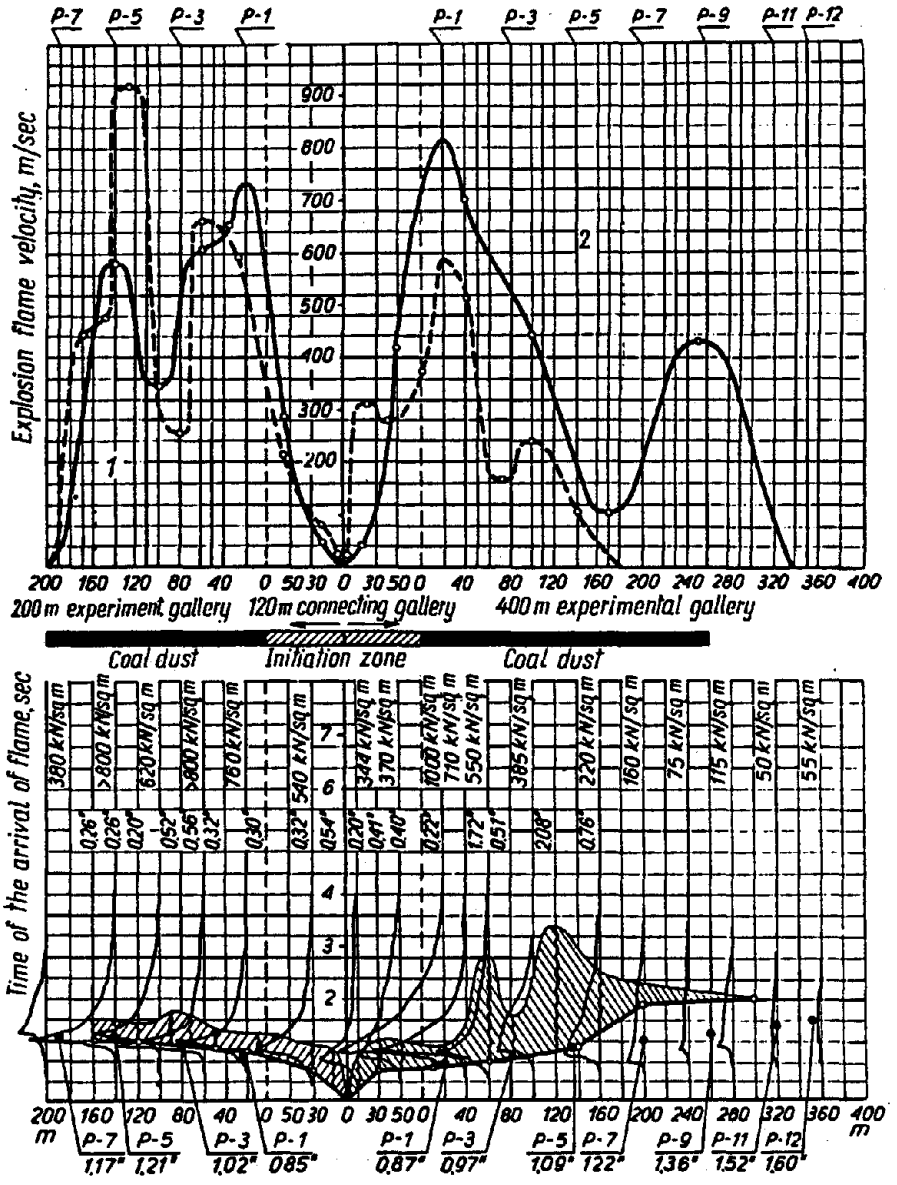


Fig. 9.33. A diagram of a two-directional explosion No. 1150 of the *d*85 coal dust, $n = 60\%$, initiator in the middle of the connecting gallery; stone dust barriers distributed: at 30 m distances in the 400 m gallery, $Q_v = 0.5$ kg/cu m; at 30 m distances in the 200 m gallery, $Q_v = 0.62$ kg/cu m; *1* — from 20 to 190 m stone dust barrier of 7 shelves at 30 m distances, $Q = 105$ kg/sq m; *2* — from 20 to 350 m stone dust barrier of 12 shelves at 30 m distances, $Q = 150$ kg/sq m. Symbols as in Fig. 6.4.

barriers. This explosion has been stopped in both galleries, the distance between the shelves being equal to 30 m and the value of Q_v — about

0.6 kg/cu m. It ought to be mentioned, however, that in both galleries the flame of the explosion had traveled over long gallery stretches before the explosion was stopped. Undoubtedly if the distances between the shelves were smaller, corresponding to the value of $Q_v = 1$ kg/cu m, the stopping of the explosion would have been accomplished within shorter stretches.

In practice the distance between the shelves depends upon the cross section of the gallery and upon the gallery's type according to standards. For instance, in galleries of a rectangular cross section, when the shelves are 50 cm broad, for the No. 2 cross section according to the standard specification PN-53/MG, the distances between the shelves ought to be 14 m. For the No. 9 cross section the distances are set at 15 m. In general for galleries with timber supports the distances between the shelves for the separate cross section numbers differ only slightly always, however, in keeping with the condition that Q_v should be equal to 1 kg/cu m. These distances are smaller, of course, when the shelves used are 35 cm broad. For the cross sections mentioned above these distances would have amounted to 8 m.

With yieldable arches and the timber frame size No. 1 according to the standard specification PN-55 the distance between 50 cm shelves ought to be about 16 m. For the timber frame size No. 10 this distance ought to be 10 m. The above figures are given here by way of examples.

The distance between the barrier units depends upon the cross section of the gallery and upon the values of Q_1 and Q_v. For a given cross section of a working, assuming that the value of $Q_v = 1$ kg/cu m, the distance between the barrier units depends only on the magnitude of Q_1 and is approximately equal to this magnitude.

9.1.12.4. Investigations on the effectiveness of barriers of shortened shelves placed unsymmetrically in a part of the cross section of galleries. Side barriers. These investigations are described in all particulars in publications [36] and [54]. Their purpose had been to find whether the coal dust cloud formed through the action of an unsymmetrical barrier will reach, in a state of sufficient concentration, the part of the gallery's cross section not occupied by the barrier. The investigations in question were of a considerable practical importance on account of the necessity to provide a free passage for men without making them to bend under the barrier which is a very tiresome proceeding, particularly in low galleries.

The shortened shelves, jointly called the side barrier, are placed in the manner shown in Fig. 9.34. The investigations were carried out in a rectilinear gallery, as well as beyond a bend, a wide range of different

explosions having been made use of, from very weak to very violent ones, with various initiators.

The barriers had been placed in a rectilinear gallery at the distances of 40, 60, 100, 160 and 200 m from the gallery's face, and of 20, 60, 100 and 120 m beyond the two-directional bend of galleries. In the course of these investigations the value of Q_v has been varied within the limits of 1.36 and 2.73 kg/cu m.

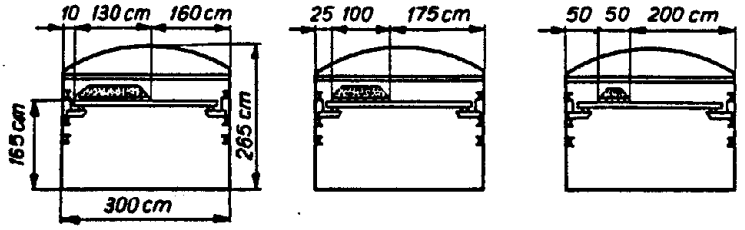


Fig. 9.34. Unsymmetrical location of side shelves in a half of the cross section of the 400 m experimental gallery.

The results of the tests have demonstrated that the disposition of the shelves, in such a way as to leave half of the gallery's cross section entirely free of shelves, did not cancel the effectiveness of the barriers — that is, the stone dust was still effectively dispersed laterally from the shelves in the large part of the gallery unoccupied by them. Such barriers, however, were found to be less effective than the ones in which the shelves were placed symmetrically in the gallery's cross section, which means merely that the side barriers required a larger quantity of stone dust to be able to stop an explosion. Though the quantities of stone dust on a barrier Q were found to be smaller under the conditions of investigations than the quantities required by regulations, yet it would not be correct to conclude from the above findings that in practice one could use shelves as short as 50 cm placed in a half of the cross section of a working.

Tests carried out with shortened shelves beyond the bends have produced even slightly better results than the tests in the rectilinear gallery. This is explained by the fact that turbulence conditions are better when explosions are initiated in the parellel gallery and the blast of the explosion passes through two bends and then enters the 400 m experimental gallery.

The effectiveness of barriers composed of shortened shelves, placed unsymmentrically in a working and leaving a free space for the traffic of men, can be tremendously enhanced by stone dusting of the zone in which a barrier of this type is located at least so as to make $n = 85$ percent, and by the use of so-called sidewall shelves. The sidewall shelves, of timber or

of incombustible material, are placed lengthwise on the side of the gallery unoccupied by the barrier. Stone dust is loaded on these shelves. During explosions they are not moved, as a rule, but the blast raises the stone dust from their surfaces. The quantity of the dust so raised depends, naturally, on the violence of the blast. These shelves ensure the presence of stone dust close to the sidewall ready to be dispersed by the explosion exactly in the space not occupied by the barrier. The breadth of the sidewall shelves ought to be 15 to 20 cm. If the sidewall shelves are placed at distances of 25–30 cm the breadth of the shelves can be reduced to from 8 to 12 cm, but then the number of such shelves must be correspondingly greater than that of the shelves 15 to 20 cm broad. The sidewall shelves should be placed along the whole sidewall. The quantities of stone dust deposited on sidewall shelves ought to be as large as possible. Since sidewall shelves are narrow the depositing of stone dust on them is effected in a very simple way, namely, during the dusting of the sidewall with stone dust; this dust is put at the same time on the sidewall shelves.

The effectiveness of sidewall shelves, and that of the dusting of the zone with stone dust, are illustrated by the following results obtained in the 200 m gallery under conditions of violent explosions, with the use of side barriers and leaving a free passage of 90 to 100 cm.

The quantities of limestone dust Q_{II} sufficient for stopping the explosion amounted to — with the employment of:

— side barriers alone $Q_{II} = 200$ kg/sq m,
— side barriers and sidewall shelves $Q_{II} = 170$ kg/sq m,
— side barriers and stone dusting of the zone of the barrier bringing the n up to 80% $Q_{II} = 120$ kg/sq m,
— side barriers with sidewall shelves and the dusting of the barrier zone up to $n = 80\%$ $Q_{II} = 85$ kg/sq m,

Altogether the investigations demonstrated, as one can see from the figures given above, that the dusting of the barrier zone with stone dust is more effective than the use of sidewall shelves. These shelves, however, aid in the accurate dusting of the sidewall since a large quantity of stone dust thrown on the sidewall remains on the shelves. Besides, the sidewall shelves can be easily controlled.

According to regulations ordinary barriers placed symmetrically ought to consist of shelves the length of which must amount to at least 65 percent of the maximum width of the working in which the barrier is situated. When the length of the shelves is smaller than indicated above the barrier is called a side barrier an it can be placed unsymmetrically.

According to the results of the tests the use of side barriers, in which the shelves are of a length equal at least to 50 percent of the width of the working, is permissible whenever necessary provided of course that the

dusting with stone dust of the barrier's zone, at least in the measure which will bring the value of n to 85 percent, will be executed and the sidewall shelves will be used. The prescribed quantity of stone dust ought to be put on the barrier itself (that is, on the ordinary shelves which will be set in motion by the explosion) and the stone dust deposited on the sidewall shelves during the dusting of sidewalls should be regarded, of course, as the additional quantity of stone dust. When these requirements are satisfied side barriers possess a sufficiently high level of confidence.

Sidewall shelves can be supplemented with shelves carrying stone dust built-in between the intermediate props. This method is shown in Fig. 9.35*a* representing a photograph of a side barrier supplemented by sidewall shelves. The shelves between the intermediate props were indicated since the shelves of the side barrier had been too short.

The picture in Fig. 9.35*b* represents a photograph of side barrier with sidewall shelves along the sidewall only.

Fig. 9.35. Side barriers: *a* — a side barrier with lateral shelves and with shelves between intermediate props; *b* — side barrier with one-sided lateral shelves.

9.1.12.5. The problem of protecting low and wide galleries by barriers. Lately a pressing problem faced the world coal mining industry, namely, the problem of protecting with barriers such galleries that are low (about 150 cm) and wide (about 500 cm).

Ordinary stone dust or water barriers cannot be placed in such workings for obvious reasons. The only thing to be done is to employ side barriers. Unfortunately no basic investigations were carried out on this problem.

In the *EM Barbara* numerous experiments were carried through with side barriers as described here very concisely in Section 9.1.12.4.

Unfortunately, the experimental gallery in the *EM Barbara* is only 300 cm wide. The width of this size is too small to test the effectiveness of the lateral dispersion of either stone dust or water according to the assumptions set forth. The special experimental gallery of the cross section measuring 150×500 cm is now in the course of construction.

Investigations which were to correspond to the above indicated conditions were carried out only in the *EM Tremonia* in the Federal Republic of Germany [124].

The investigations in question were carried through in a gallery 150 cm high, 450 cm wide and 95 m long. Water barriers only were used consisting of 80 liter containers. The quantities of water used in the experiments were varied from 100 to 170 liters/sq m. Only violent explosions were realized their flame velocity approaching the sonic velocity. The pressures recorded ranged up to 500 kN/sq m.

It has been found that, under such conditions, coal dust explosions can be stopped. Unfortunately no investigations were carried out so far in the conditions of very weak explosions in which side barriers, situated in very wide workings, can be ineffective because the lateral dispersion of water or stone dust, considering the small energy of the blast, may be insufficient.

In view of the urgent necessity of making a close study of the effectiveness of the lateral stone dust dispersion by the barriers, investigations were undertaken in the *EM Barbara* in a large gallery its cross sectional area being equal to 7.5 sq m, and its breadth to 3 m. Side barriers were being reduced down to the length of 80 cm and the shelves were placed consecutively at different heights. The distance of the side barrier from the opposite sidewall amounted to 200 cm.

Sidewall shelves with stone dust were placed on the side of the gallery opposite to that occupied by the barrier.

The tests were carried through with the weakest coal dust explosions. In several of the experiments these explosions have been stopped with quantities of stone dust on the barrier amounting to 100–150 kg/sq m.

The results obtained up to the present time can be viewed as being good particularly on account of the fact that in the zone of the barrier, as well as outside this zone, pure $d25$ coal dust had been deposited on roof bars; the presence of this dust facilitated considerably the development of explosions. But the results to which reference is made here ought to be treated as provisional: conclusive results can be obtained from experiments made in a gallery 500 cm broad, 150 cm high and 180 m long. In Fig. 9.36 a photograph is shown of the side barriers, discussed here, together with sidewall shelves in te 400 m experimental gallery.

Fig 9.36. A side barrier 80 × 80 cm with lateral shelves in the 400 m experimental gallery 3 m broad, the cross sectional area of which equals 7.5 sq m.

9.1.12.6. Investigations on the influence of lowering the location of the barrier on its effectiveness. The aim of this work has been to find how effective is the dispersion of stone dust upward — that is, above the shelves; apart from being of a basic importance this problem possesses a direct, practical importance because it frequently happens in mines that the upper part of the cross section of a working is occupied by air ducts and other pipelines. The ways in which the barrier shelves were located in these investigations are shown in Fig. 9.37. The tests were made under five different explosion conditions including also the tests with a double bend of the gallery.

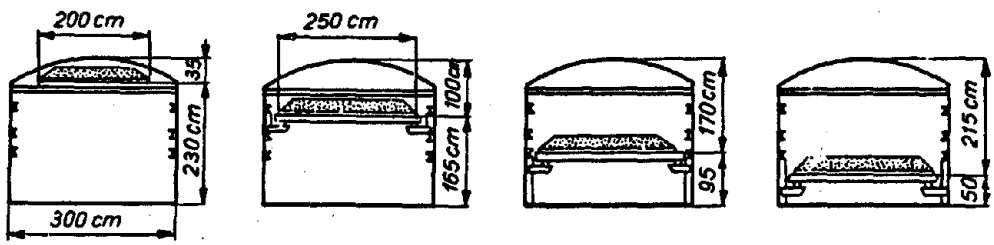


Fig. 9.37. The location of the barrier shelves at varying heights in the 400 m experimental gallery.

It has been demonstrated in the course of these investigations that with very strong explosions, even when the shelves were placed very low — that is, when the distance between the frame of the shelf and the roof amounted to 215 cm, the stone dust has been still effectively dispersed throughout the gallery's cross section. Under such conditions the barriers

did stop the explosions even with quantities of stone dust considerably smaller than those required by regulations.

With weak explosions the influence of the effectiveness of barriers of the increased distance between the barrier and the roof has been, naturally, considerably greater. Nevertheless even in such conditions the barriers stopped the explosions with quantities of stone dust, though larger than in the cases of strong explosions, yet still below the regulation requirements. Of course such an extremely low location of the shelves is out of the question in practice. In the investigations discussed here one of the aims had been the ascertainment of the way in which the dust is dispersed in the upper part of the working, above the shelves, in connection with the employment of barriers in galleries higher than the experimental gallery.

From the described investigations an important practical conclusion can be drawn, namely, that in cases of necessity it is permissible to locate barriers lower than this is generally done up to the present; with the reservation, however, that the distance between the base of the shelf and the roof should not amount to less than 100 cm.

9.1.12.7. Storied barriers and the possibilities of stopping firedamp explosions. As evidenced by investigations described in previous sections ordinary barriers, composed of shelves placed near the roof, disperse stone dust adequately in the entire cross section of the working. It is, however, quite understandable that if shelves were placed one above another, from the floor to the roof, at reasonable distances then the blast would disperse the stone dust with considerably better accuracy in the cross section of the working and, besides, the density of the stone dust cloud would have to be greater than in the case of an ordinary barrier. Such barriers are called storied barriers. The dispersion of the storied shelves in the experimental gallery is shown in Fig. 9.38. According to the number of shelves placed one above another the barriers are described as the two storey, three storey, etc. barriers. Ordinarily several sets of storied barriers are used placed at small distances from each other. They are denoted, for example, by the symbol 4×3 indicating that four sets of three storey barriers are being employed.

In the *EM Barbara* systematic investigations were carried out on the use of storied barriers [26]. Such barriers are actually very effective. They were employed in the *EM Barbara* to stop explosions at the outlet of the experimental gallery in order to restrict the destructive effects of the explosion blast bursting forth to the surface. Stone dust dispersed in the form of a very dense cloud offers a considerable resistance to the blast and very effectively extinguishes the flame.

Storied barriers, unfortunately, offer a very considerable resistance also to the air flow and practically close the passage through the working. The last named disadvantage of storied barriers can be removed by using such barriers with a passage as shown schematically in Fig. 9.39.

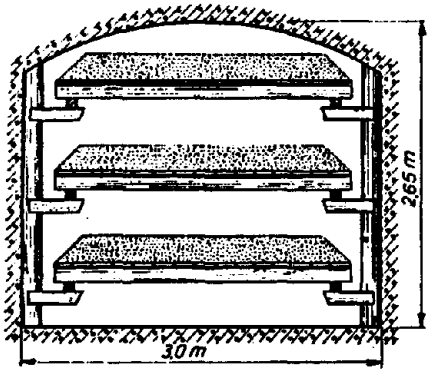


Fig. 9.38. The position of the three storey barrier in the 400 m experimental gallery.

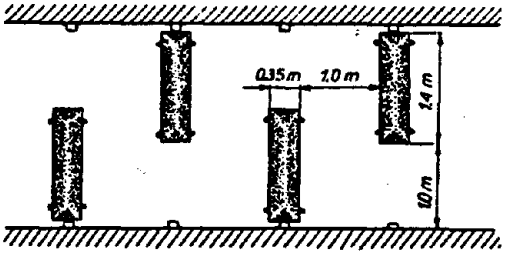


Fig. 9.39. A schematic diagram of a storied barrier with a passage (top view).

The proof of the very good dispersion of the dust over the entire cross section of the working was supplied by the successful experiment of stopping a coal dust explosion with a pure coal dust. This is possible provided that the coal dust concentration exceeds the upper explosive limit of this dust.

In the experiment mentioned above explosion No. 1421 of coal dust, shown in Fig. 9.40, was stopped by a storied barrier 3 × 3 containing

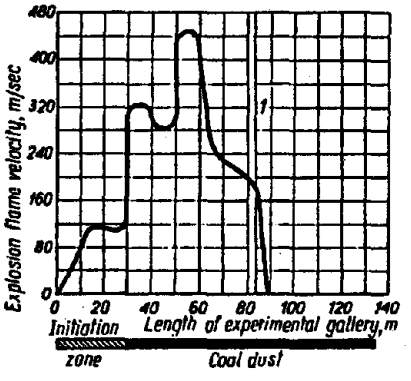


Fig. 9.40. A diagram of explosion No. 1421 of the d85 coal dust, $n = 60\%$, initiator 30mPII; *1* — the storied barrier 3 × 3, 500 kg of stone dust, $Q = 100$ kg/sq m of pure coal dust stopped this explosion.

500 kg of pure coal dust $Q = 100$ kg/sq m. The barrier had been placed at the distance of 80 m from the gallery's face. In practice, naturally, coal

dust will never be used on barriers. The experiment in question served to show how properly the dust has been dispersed in the whole cross section of the working and to demonstrate that, on the scale of a mine, it is possible to realize a dispersion of coal dust in excess of its explosive concentration.

On account of the fact that they disperse the dust so well the storied stone dust barriers are considerably more effective than the ordinary barriers.

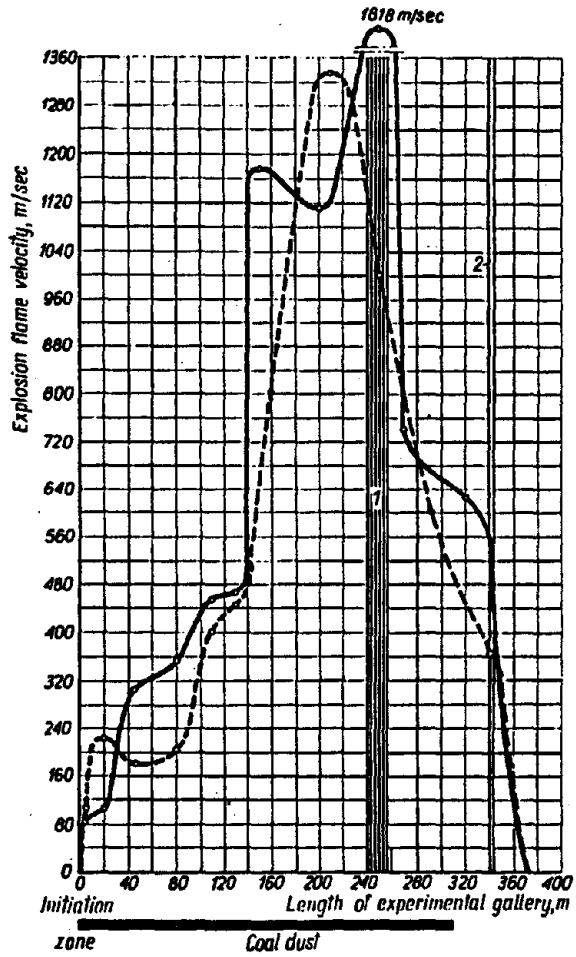


Fig. 9.41. A diagram of explosion No. 231 of the natural d25 coal dust, $n = 20\%$, initiator 50 cu m CH_4 (9.5%), ignition 750 g of gunpowder; *2* — a storied protecting barrier 2 × 3, 675 kg of stone dust, $Q = 90$ kg/sq m stopped this explosion which was not stopped by *1* — an ordinary barrier, of 6 shelves, 675 kg of stone dust, $Q = 90$ kg/sq m.

It has already been mentioned that storied barriers were used in the investigations carried out in the experimental gallery as a protection against the explosion effects on the surface. Storied barriers were placed beyond the examined zone. Stoppages of explosions were achieved with stone dust quantities much smaller than those required by regulations even in such cases in which the flame velocity before the barrier amounted to about 1000 m/sec. As an illustration in Fig. 9.13*a* an example was given of explosion No. 99 stopped with a storied barrier 3 × 3; Q = 135 kg/sq m. Another example of the effectiveness of storied barriers is given in Fig. 9.41. It is generally known that ordinary stone dust barriers are employed to stop coal dust explosions: they do not stop firedamp explosions. However, when the quantity of stone dust on the barrier is large and the firedamp explosion is not too strong the explosion can be stopped, or its range can be materially restricted. Storied stone dust barriers, on the other hand, can stop or restrict firedamp explosions more effectively provided that they contain a large quantity of stone dust. The results of these investigations are given in the publication [26]. As an illustration of the way in which storied barriers acted on explosions of 75 cu m of methane in Fig. 9.42*a* and *b* examples are given of such explosions being stopped by storied barriers 2 × 3 (Q = 100 kg/sq m and Q = 85 kg/sq m) at the distance, respectively, of 20 and 40 m from the gallery's face. These

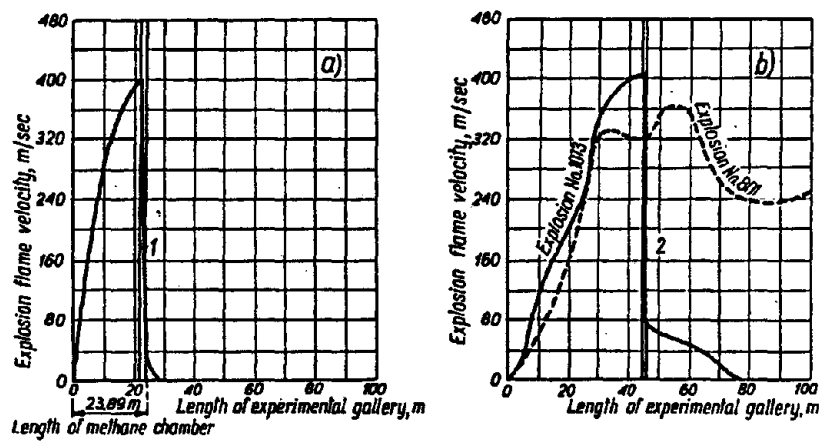


Fig. 9.42. Diagrams of explosions: *a* — explosion No. 586, 75 cu m CH_4 (9.5%), ignition 750 g of gunpowder in the 100 m surface experimental gallery; *1* — the storied barrier, 2 × 3, shelves, 300 kg of stone dust, Q = 100 kg/sq m stopped this explosion; *b* — explosion No. 1073, 75 cu m CH_4 (9.5%), ignition at the gallery's face; *2* — the storied barrier, 2 × 3, shelves, 250 kg of stone dust, Q = 85 kg/sq m stopped this explosion (the dotted line represents a diagram of explosion No. 801, 75 cu m CH_4 (9.5%) with no barrier).

experiments were carried out in a 100 m surface experimental gallery of a cross sectional area equal to 3 sq m.

A storied barrier which is to stop an explosion of methane or to restrict its range should not be situated in a methane zone. For it is more difficult to stop a methane explosion with a storied barrier if the barrier is placed in a methane zone; in such a case the quantity of stone dust on the storied barrier has to be larger than that required by regulations for methane seams.

Their great effectiveness notwithstanding, storied barriers are very seldom used because of their disadvantages in practical application mentioned in the beginning. Storied barriers are employed rather in the cases of serious and sudden hazards only in order to get a protection against a possible development of a coal dust explosion initiated by the ignition of a sudden, dangerous accumulation of methane or by the ignition of flammable fire gases.

Taking into account the fact that storied barriers are used in the cases in which there is a direct hazard of a serious explosion, an even larger quantity of stone dust on the barrier is required than that normally fixed for methane seams, namely, 600 kg/sq m.

9.1.13. Stopping by stone dust barriers of the *EM Barbara* type of the weakest possible coal dust explosions initiated by the ignition of the methane roof layer

9.1.13.1. General information. In the course of the investigations on the roof layers of methane (Sections 5.2 and 5.3) it has been established that the ignition of the roof layers of methane can act as the initiator of the weakest possible coal dust explosions. Figure 9.43*a* and *b* presents examples of such weakest explosions of coal dust. In the diagrams in question equations are given expressing the dependence of the distance s upon the time t, the value of the acceleration a and the mean value of the velocity of the flame v_{sr}.

After the know-how had been experimentally acquired of realizing the weakest coal dust explosions, the effectiveness of barriers in stopping such explosions has been tested, of course. These tests were quite needful considering that such explosions do occur in the mining practice. An apprehension may be felt that the barriers might not be put into action in consequence of the dynamic pressures of the blast being too low. Such facts were repeatedly observed in foreign mines.

The problem of the weakest possible coal dust explosions has been discussed in Chapter 5. In the same chapter the results were given of

investigations on the dependence of the dynamic pressure of the blast upon the velocity of the flame of very weak coal dust explosion.

In consequence of these investigations regression equation has been formulated expressing the dependence of the mean dynamic pressure p millibar upon the flame velocity v m/sec

$$p = 0.4543 \cdot v^{0.8352} \tag{9.5}$$

The coefficient of correlation $r_{pv} = 0.698$

The mean error of the regression $S_{pv} = 8.5$

Analogously a regression equation has been formulated expressing the dependence of the maximum dynamic pressure P millibar upon the mean velocity of the flame v_w m/sec

$$P = 0.3949 \cdot v_w^{1.0653} \tag{9.6}$$

The coefficient of correlation $r_{pw} = 0.862$

The mean error of the regression $S_{pvw} = 15.0$

The dependences expressed by the above equations were presented graphically in Fig. 2.19. In Table 2.8 dynamic pressures p and P were given for the mean flame velocities from 20 to 100 m/sec.

Knowing the dynamic pressure that will suffice to put into action a barrier of a given type one is able to foresee whether the barrier in question could fail to act effectively in the case of a very weak coal dust explosion.

In Table 9.2 are listed the results of investigations on the lowest dynamic pressures which suffice to put into action barriers of several types. A schedule of the results pertaining to the *EM Barbara* type barriers — selected from Table 9.2 — permits to conclude that a barrier of this type would be put into action by the weakest explosions of coal dust.

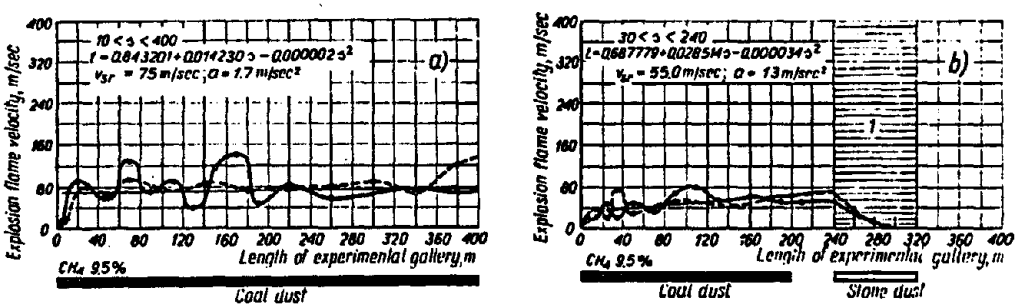


Fig. 9.43. Diagrams of explosions: *a* — explosion No. 1320 of the natural d25 coal dust, n = 20%, initiator — a roof layer of methane 9.5% CH_4, V_M = 4 cu m, H = 12.2 cm, L = 30 m; *b* — explosion No. 1182 of the d25 natural coal dust, n = 20%, initiator — a roof layer of methane 9.5% CH_4, V_M = 4 cu m, H = 12.2 cm, L = 30 m; *1* — protecting zone of stone dust, 1652.5 kg of the dust, Q = 220.3 kg/sq m.

Coal dust explosions in which the mean flame velocities are so low cannot be easily realized on longer distances such as, for instance, in the case presented in Fig. 9.43*a*. It is much easier to realize explosions developing in a similar manner on relatively short sections between the gallery's face and the barrier placed at a small distance from the face. In the zone of the barrier and beyond this zone more dangerous coal dust may be present which can cause a very strong propagation of the explosion if the barrier should fail to act effectively because of the explosion being very weak in the initial section.

9.1.13.2. The results of the investigations on the effectiveness of barriers under conditions of the weakest coal dust explosions. Altogether 25 experiments were made with the *EM Barbara* shelves, 35 as well as 50 cm broad.

Under the described conditions of the weakest coal dust explosions 25 experiments had been carried through during which the effectiveness was tested of the *EM Barbara* type barriers composed of 35 and 50 cm shelves. The barriers were placed at the distance of 50, 100 and 200 m from the gallery's face.

In 12 of these experiments the dust conditions were procured which made possible the development of the weakest coal dust explosion over the entire length of the 400 m gallery. In all these cases the barriers stopped the explosions with quantities of stone dust much smaller than those required by regulations for nonmethane seams. The values of Q_{II} oscillated from 58 kg/sq m at the distance of 60 m from the face of the gallery to 120 kg/sq m at the distance of 200 m from the face. Up to the distance of 60 m from the gallery's face the mean velocity of the flame v_{sr} amounted to 50.6 m/sec, at 100 m v_{sr} amounted to 61.4 m/sec, and at 200 m — 84.6 m/sec.

Depending on the distance from the gallery's face at which the measurements were taken the mean dynamic pressures p amounted mostly to 2–3 kN/sq m; at the distance of 60 m the pressures were 3.5 kN/sq m; and at the distance of 100 m — 4.7 kN/sq m.

As an illustration of this series of experiments in Fig. 9.44*a* a diagram is shown of explosion No. 1227 stopped by the barrier $Q = 120$ kg/sq m placed at the distance of 200 m from the gallery's face.

In the other experiments, both in the zone of the barrier and beyond this zone, pure d85 coal dust had been spread and this very distinctly facilitated the passing of the explosion through the barrier and the development of the explosion. In the conditions above described in one case the barrier did not stop the explosion at the distance of 60 m from the gallery's face with $Q = 150$ kg/sq m. It should be remembered that this quantity is smaller than that prescribed by regulations. The mean

flame velocities v_s, up to 60 m and up to 200 m from the gallery's face amounted to 45.7 and 111.6 m/sec, respectively.

The mean dynamic pressures p amounted to 3.4 and 4.97 kN/sq m at the distances of 60 and 200 m from the face of the gallery, respectively.

As examples illustrating this series of experiments in Fig. 9.44b a diagram of explosion No. 1250 is given, this explosion having been stopped with the barrier Q = 150 kg/sq m placed at the distance of 60 m from the face of the gallery, and in Fig. 9.44c a diagram is shown of explosion No. 1269 stopped by the barrier Q = 150 kg/sq m placed at the distance of 200 m from the gallery's face.

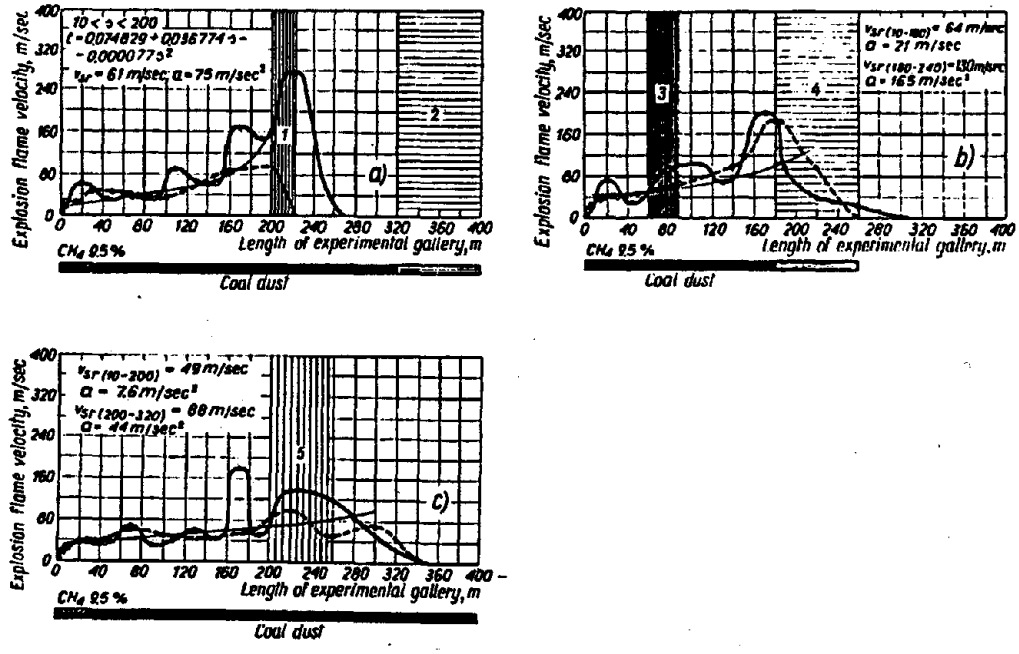


Fig. 9.44. Diagrams of explosions: *a* — explosion No. 1227 of the d50 coal dust, n = 18.7%, initiator — a roof layer of methane 9.5% CH_4, V_M = 4 cu m, H = 12.2 cm, L = 30 m; *1* — the barrier of 8 shelves, 900 kg of stone dust, Q = 120 kg/sq m stopped this explosion; *2* — stone dust protecting zone, 1652.5 kg of dust, Q = 220 kg/sq m; *b* — explosion No. 1250 of the d25 natural coal dust, n = 20.6% and of the d85 coal dust, n = 15.6%, initiator — a roof layer of methane; *3* — the barrier of 18 shelves, 1125 kg of stone dust, Q = 150 kg/sq m did not stop this explosion; *4* — stone dust protecting zone, 1652.5 kg of dust, Q = 220 kg/sq m; *c* — explosion No. 1269 of the d25 coal dust, n = 35%, and of the d85 coal dust, n = 16.7%; *5* — the barrier of 10 shelves, 1125 kg of stone dust, Q = 150 kg/sq m stopped this explosion.

9.1.13.3. A summary of the results of investigations. Recapitulating the results of the investigations on the effectiveness of barriers of the

EM Barbara type in conditions of particularly weak explosions, initiated by the ignition of the roof accumulations of methane, it ought to be stated that such explosions are easily stopped if the conditions of coal dust in the whole gallery permit the realization of a weak explosion. However, if a very dangerous coal dust is present in the zone of the barrier, or outside of this zone, the stopping of the explosion becomes more difficult. It is exactly in such conditions that one of the explosions did pass through the barrier. Again it ought to be noted that the quantity of stone dust on this barrier was smaller than that required by regulations.

In the course of these investigations in many cases the explosion between the gallery's face and the barrier had been so weak that its flame did not reach the barrier. Yet, even in these cases, a considerable majority of the shelves were thrown down. It happened now and again that the shelves were not overturned in the cases in which the flame did not reach the barrier but only when the depth of the barrier's frame was smaller than 20 cm.

The ease with which the shelves could be put into action was bound up with their breadth. Naturally 35 cm shelves were put into action easier than 50 cm ones.

9.2. WATER BARRIERS

9.2.1. General information

The idea of water barriers has to be attributed to the French scientist cited here frequently, namely, to Taffanel. The principle on which they operate is very simple. If containers filled with water are placed on the way of the development of a coal dust explosion, and the explosion blast will cause a good dispersion of water, then the dispersed water should stop the coal dust explosion by extinguishing the explosion flame in consequence of the high specific heat and the heat of evaporation of water and, particularly, because of the reduction of the volume concentration of oxygen through the water vapor. The means which Taffanel had at his disposal did not suffice to have this type of barriers introduced for use in the mining practice. It was in relatively recent times that the thought of using water barriers caught the interest of specialists again in connection with the great progress in the production of plastics — a good material for the manufacture of water containers. Such containers can be manufactured from polyvinyl chloride, polystyrene and foamed polystyrene or from other plastics. Particularly numerous investigations on the effectiveness of water barriers were carried out in the *EM Barbara*,

in the *EM Tremonia* in the Federal Republic of Germany, and in the Experimental Station at *Dortmund*.

Water barriers are in many points superior to stone dust barriers. One of their most important advantages consists in this that the necessary water is present in the pipelines in very many mine workings and, consequently, there is no need of bringing it down in contrast with the fact that stone dust must be brought down from the surface. Besides, water does not lose its properties with the passage of time in contrast with the ordinary (not waterproof) stone dust which loses its dispersibility, especially in humid conditions. Though water will evaporize, particularly when the relative humidity of the air is comparatively low, yet the level of water in the containers can be easily controlled and there is no difficulty connected with the refilling of the containers.

In humid or wet conditions water barriers display a more stable effectiveness than stone dust barriers. Although a waterproof stone dust will retain its properties over a period of even three months when deposited in very humid conditions, yet it is not used willingly on account of its very high dispersibility which makes it unpleasant even during the work of putting it on the barrier shelves.

As one of the merits of water barriers until quite recent times had been regarded, and even now is regarded, the more easy distribution in mine workings of water containers than the distribution of shelves on which stone dust is deposited. This question will be elucidated in one of the next sections since it was found that this is a very limited advantage.

Naturally the most essential question is that of the effectiveness of water barriers in general, and in comparison with the effectiveness of stone dust barriers. Very many experiments were dedicated to the elucidation of this question.

The process itself of putting into action water barriers on the one hand, and stone dust barriers on the other hand, discloses the great difference between them.

As one knows stone dust barriers, for example, of the *EM Barbara* type, are put into action by the blast which sets in motion the separate elements of the barrier causing in this way the dispersion of stone dust (see Section 9.1.5). Consequently, the shelves of the barriers of this type cannot be fixed rigidly. The problem of putting water barriers into action is quite different. The basic elements of the water barriers are containers, examples of which are shown in Fig. 9.45 and in Fig. 9.46 illustrating the way of arranging containers held by framelike holders in a mine gallery. In Fig. 9.45 framelike holders are shown and the way in which they hold the containers. Containers can be suspended from the support or from the roof in the ways shown in Fig. 9.47. The possibility of suspending water

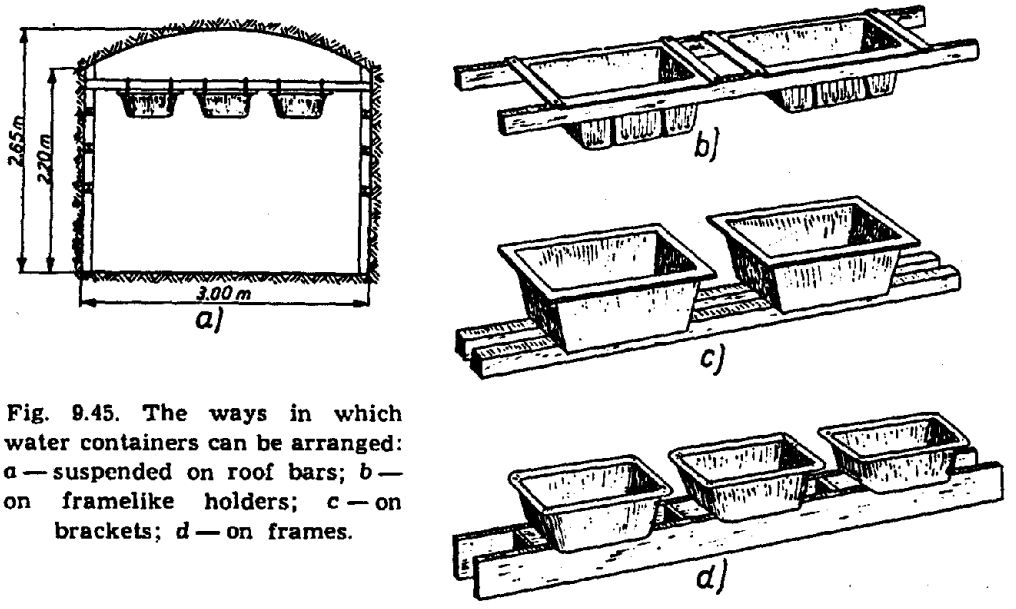


Fig. 9.45. The ways in which water containers can be arranged: *a* — suspended on roof bars; *b* — on framelike holders; *c* — on brackets; *d* — on frames.

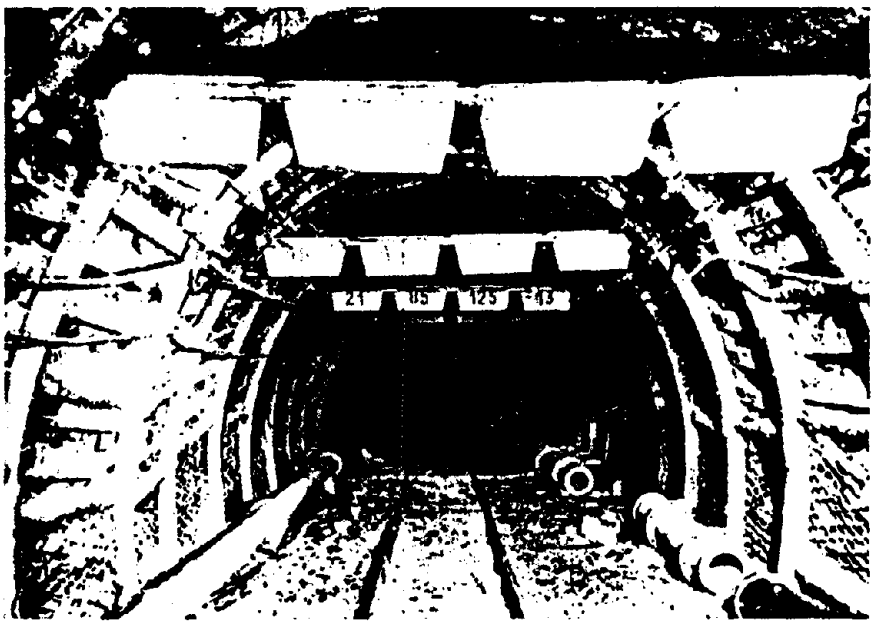


Fig. 9.46. Containers placed in the *Mortimer-Porąbka* mine.

containers in various ways is a great advantage of water barriers, as it permits the distribution of the containers according to the free space in the upper part of a mine working frequently occupied with air dusts, pipelines, etc., which make it difficult to locate stone dust barriers. The

ways of placing water containers in framelike holders, and of suspending them from the support as shown in Figs. 9.46 and 9.47, depend upon the adopted principle of the functioning of water containers during explosions.

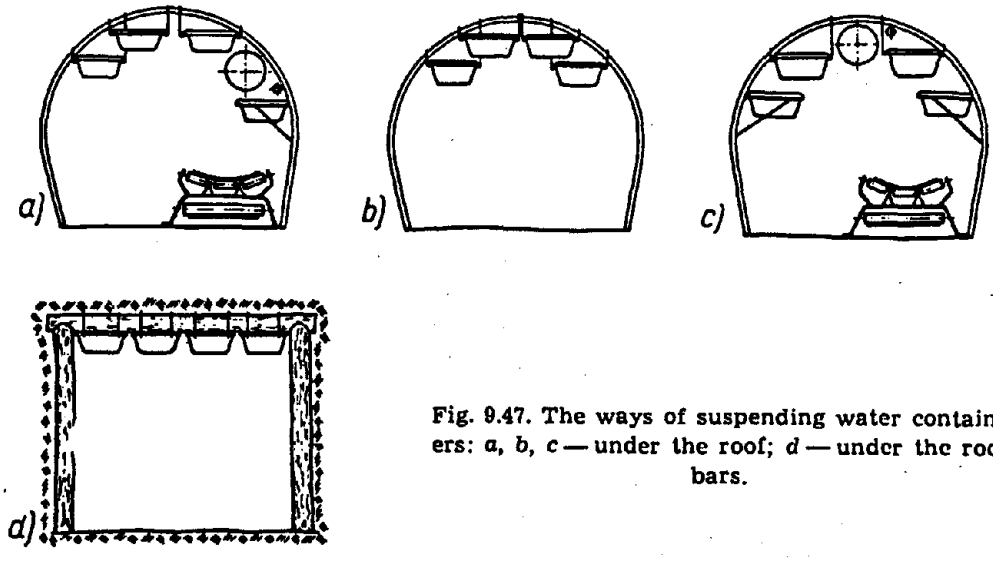


Fig. 9.47. The ways of suspending water containers: *a*, *b*, *c* — under the roof; *d* — under the roof bars.

A view had been expressed that water containers will be destroyed under the impact of the explosion blast — that is, that they will burst very quickly and be simply torn asunder, the water being dispersed at once by the blast. According to this view the rigid fixing of containers is fully justified and should give even better effects than, for instance, placing them on brackets or on rails. When the blast is sufficiently strong water barriers actually work that way. But then everything depends on the force of the blast and this, in turn, depends on the way in which the explosion develops.

9.2.2. Investigations concerning the procedure of putting water barriers into action

With reference to the remarks given in the foregoing section it can be stated that the basic datum, characterizing the functioning of a barrier of any type, is the minimum magnitude of the dynamic pressure of the explosion blast which is sufficient to put assuredly into action the particular type of the barrier. The investigations on stone dust barriers were discussed in Section 9.1.13. The results of these investigations were listed in Table 9.4. In the same table are listed the results of investigations concerning water containers manufactured in Poland from polystyrene, the

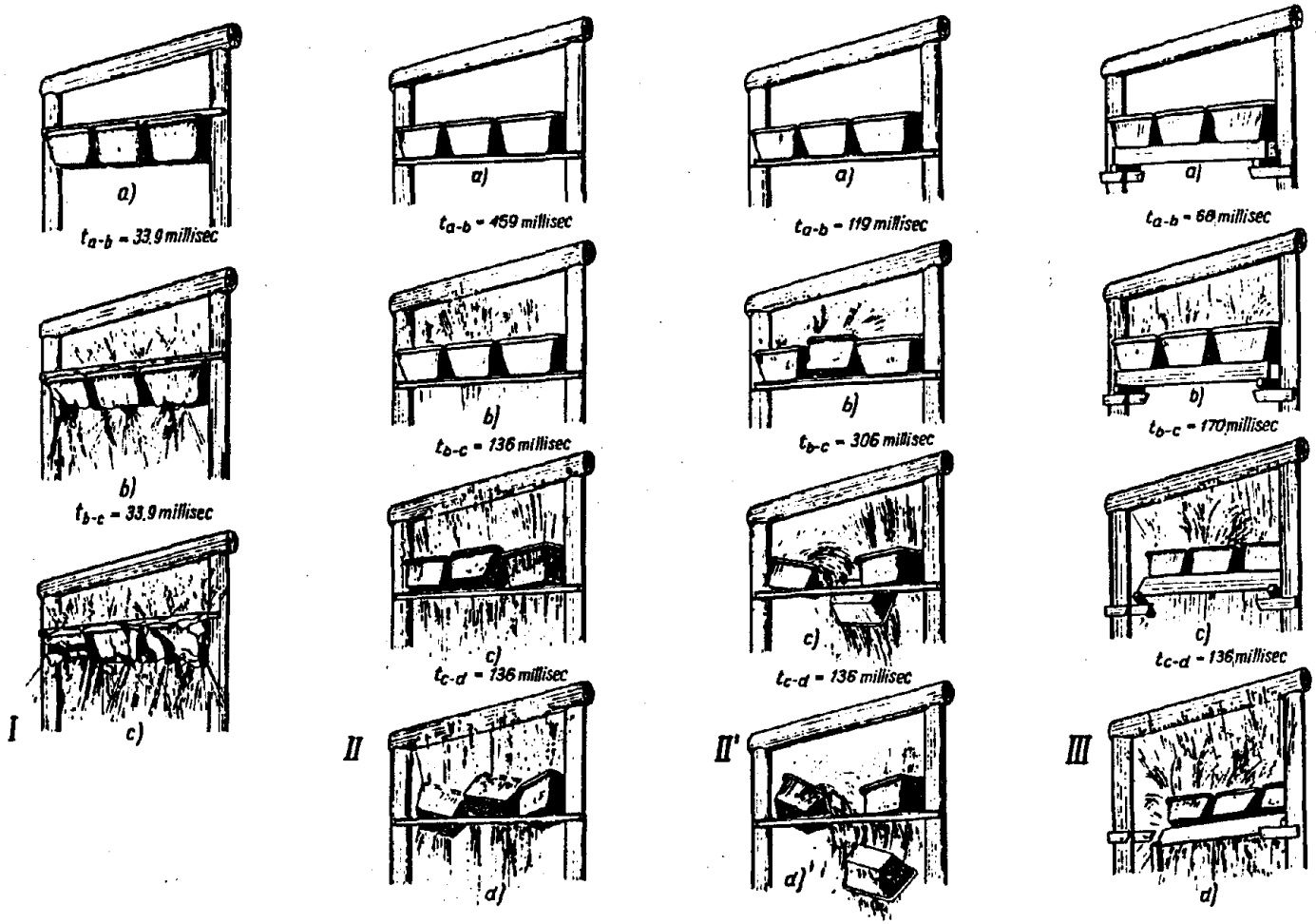


Fig. 9.48. The process of putting into action polystyrene water containers of the *EM Barbara* type 60×33×28 cm; *I* — rigidly suspended; *II*, *II'* — placed on beams; *III* — placed on frames 20 cm deep.

dimensions of which are 60×33×28 cm, suspended — and rigidly fixed — under the roof bar as well as placed on immovable beams or on such frames that are used in stone dust barriers of the *EM Barbara* type.

As the table named above shows for putting the rigidly fastened containers into action under the more favorable investigation conditions the necessary pressure amounted to at least 6.0 kN/sq m, and in the less favorable conditions as much as 15.0 kN/sq m was necessary. In other words, the necessary dynamic pressure amounted to approximately five times the pressure required for the stone dust barriers of the *EM Barbara* type. The difference in the facility with which these barriers can be put into action is, therefore, very marked. It becomes particularly evident in the case of dynamic pressures observable in weak coal dust explosions. The magnitude of these pressures was examined with special attention in the *EM Barbara*. The results of these examinations are given in Table 2.8. Taking account of the fact that during very weak coal dust explosions dynamic pressures can be much lower than 3.0 kN/sq m, it is to be expected that the rigid fastening of water containers may cause their immobility during an explosion. This has been confirmed in the course of investigations carried out in the *EM Barbara* [65]. Motion pictures were taken in the *EM Barbara* of the process of putting the water containers into action [59] same as in the case of stone dust barriers.

The process of putting into action water containers rigidly suspended, placed on beams and placed on frames is illustrated in Fig. 9.48.

The time of discharging water, in the case of rigidly fastened containers properly destroyed by the explosion blast, amounted to 190 millisec for polystyrene containers during rather weak methane explosions with the dynamic pressure equal to about 15.0 kN/sq m; when the dynamic pressures were stronger this time amounted to 70 millisec.

9.2.3. The effectiveness of water barriers

9.2.3.1. General information. The effectiveness of water barriers in stopping coal dust explosions is, naturally, their fundamental distinguishing trait of the most essential importance. In the *EM Barbara* very extensive investigations have been carried out on the effectiveness of water barriers analogous to the investigations described in Section 9.1.10. Very numerous experiments were made in this connection. Many experiments were also made in the *EM Tremonia*.

In view of the fact that stone dust barriers have been in use since many years, both in Polish and in foreign mines, the effectiveness of water barriers was compared with the effectiveness of stone barriers. Such a comparison has been the more indicated since stone dust barriers of the

EM Barbara type not only proved to be very effective during the experiments but — and this is most important — they never failed in the actual use in mines.

9.2.3.2. The effectiveness of water barriers as depending on the violence of the explosion; a comparison with stone dust barriers. It is a fact well known from the huge experience with barriers in various explosion conditions that the most decisive, as far as the effectiveness of barriers is concerned, are the extreme conditions created by the exceptionally violent explosions by the weakest possible explosions and by explosions in which the time interval between the putting the barrier into action and the arrival of the flame to the barrier is relatively very long.

Such explosions which after a slow development suddenly achieve a very great acceleration of the flame, at a very short distance from the barrier, are particularly difficult to stop.

Accordingly water barriers were carefully tested in exactly such conditions. Moreover the tests included the entire range of explosions from the weakest to the most violent ones. Most of these tests were reported upon in the already mentioned publication [53]. In the tests in question the water containers used were not only those shown in Fig. 9.45 but also primitive wooden and sheet metal containers as well as polyethylene bags, manufactured in the German Democratic Republic, filled with water.

As far as strong and very strong explosions are concerned the type of the containers did not affect at all the effectiveness of the water barriers except that the polyethylene bags proved to be unpractical. The tests were carried out also beyond the gallery bends.

The results of the comparative tests of the effectiveness of water barriers and of stone barriers, both in rectilinear galleries and beyond gallery bends, were summarized and listed in Table 9.4. This table is based on the results of 15 different series of experiments which supplied the data for making 25 comparisons between the effectiveness of water barriers and of stone dust barriers. Considering separately water barriers composed of containers which are actually most frequently used the following comparative observations have been made:

— four cases in which the effectiveness of the barriers was found to be much the same,

— five cases in which stone dust barriers proved to be distinctly more effective,

— four cases in which water barriers were slightly more effective,

— four cases in which it was impossible to determine the difference between the effectiveness of the barriers.

Generally the effectiveness of water barriers and of stone dust barriers in rectilinear galleries proved to be much the same. In all cases

in which stone dust barriers were distinctly more effective than water barriers, the barriers had been placed beyond gallery bends.

When barriers are placed at longer distance from the gallery bends the difference between the effectiveness of stone dust barriers and of water barriers gradually disappears.

As an illustration of the results of the tests of water barriers, listed in Table 9.4, in Fig. 9.49 a characteristic diagram is given of explosion No. 654. A water barrier placed beyond two gallery bends at the distance of 40 m from the face of the parallel gallery, in which the explosion had been started, did not stop this explosion in spite of the large quantity of water on the barrier, namely, $Q = 240$ kg/sq m. The explosion has been stopped only in the stone-dusted protecting zone.

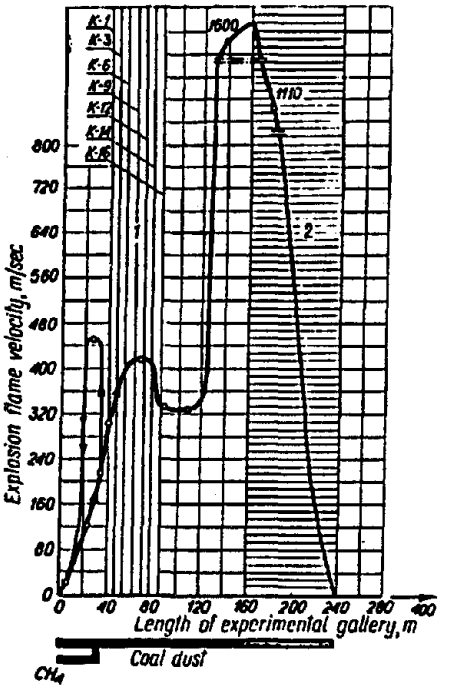


Fig. 9.49. A diagram of explosion No. 654 of the *d*85 coal dust, $n = 17.3\%$, initiator 50 cu m CH_4 in the parallel gallery; ignition with an electric detonator close to the paper partition; *1* — from 40 to 80 m water barrier, 16 sets of containers at 3 m distances, $Q = 240$ kg/sq m beyond two gallery bends; *2* — protecting zone of stone dust, $Q = 2.75$ kg/sq m. Symbols *K-1*, *K-3*, etc. mean first trough, third trough etc.

It should be mentioned that water barriers consisting of polyethylene bags, from the experimental station at Freiberg, were found not to be sufficiently effective.

9.2.3.3. The effectiveness of water barriers as depending on the time in which they are put into action. The influence of the time in which stone dust barriers are put into action on their effectiveness has been discussed in Section 9.1.11.8. Analogous tests made with water barriers showed that they behave differently from stone dust barriers [53]. Water barriers

had been placed at the distance of 100 m from the face of the gallery — that is, at the place at which the stoppage of an explosion is the easiest in cases of t_p values being normal.

The values of t_p were changed within the limits of 0.06 and 6.32 sec. The results of the experiments are presented in a graphic form in Fig. 9.50. By employing the method of the discriminant analysis the straight line *1* was determined separating the extreme values of parameters at which explosions are propagated

$$t_p = 0.008841Q + 0.58 \tag{9.7}$$

as well as the straight line *2* for the probability of 2.5 percent of explosions being propagated

$$t_p = 0.008841Q - 0.53 \tag{9.8}$$

As can be seen from the diagram (Fig. 9.50) the effectiveness of water barriers distinctly diminishes as the time of putting the barrier into action grows similarly to what had been established in the case of stone dust

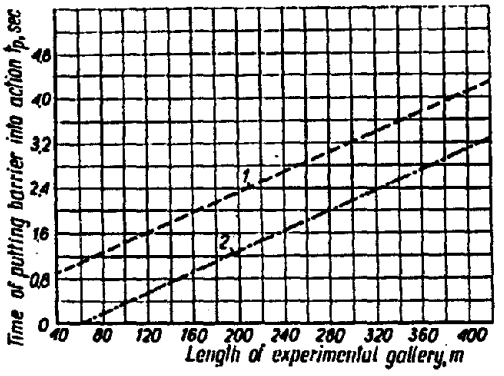


Fig. 9.50. A diagram of the effectiveness of water barriers as depending upon the time of putting the barrier into action t_p (the *d*85 coal dust, $n = 50\%$, initiator 30mPII): *1* — straight line representing equation $t_p = 0.008841\ Q + 0.58\ H_2O$; *2* — straight line representing equation $t_p = 0.008841\ Q - 0.53\ H_2O$.

barriers. By increasing the total quantity of water on the barrier Q to as high a value as 400 kg/sq m the stabilization was achieved. The stabilization in the case of stone dust barriers denoted the situation in which the load on the barrier achieved the magnitude at which the effectiveness of the barrier was no longer affected by an increase of t_p. The impossibility of achieving a similar stabilization is unquestionably a serious shortcoming of water barriers.

The results of investigations, shown in Fig. 9.50, clearly demonstrate that the effectiveness of water barriers — when the value of t_p exceeds

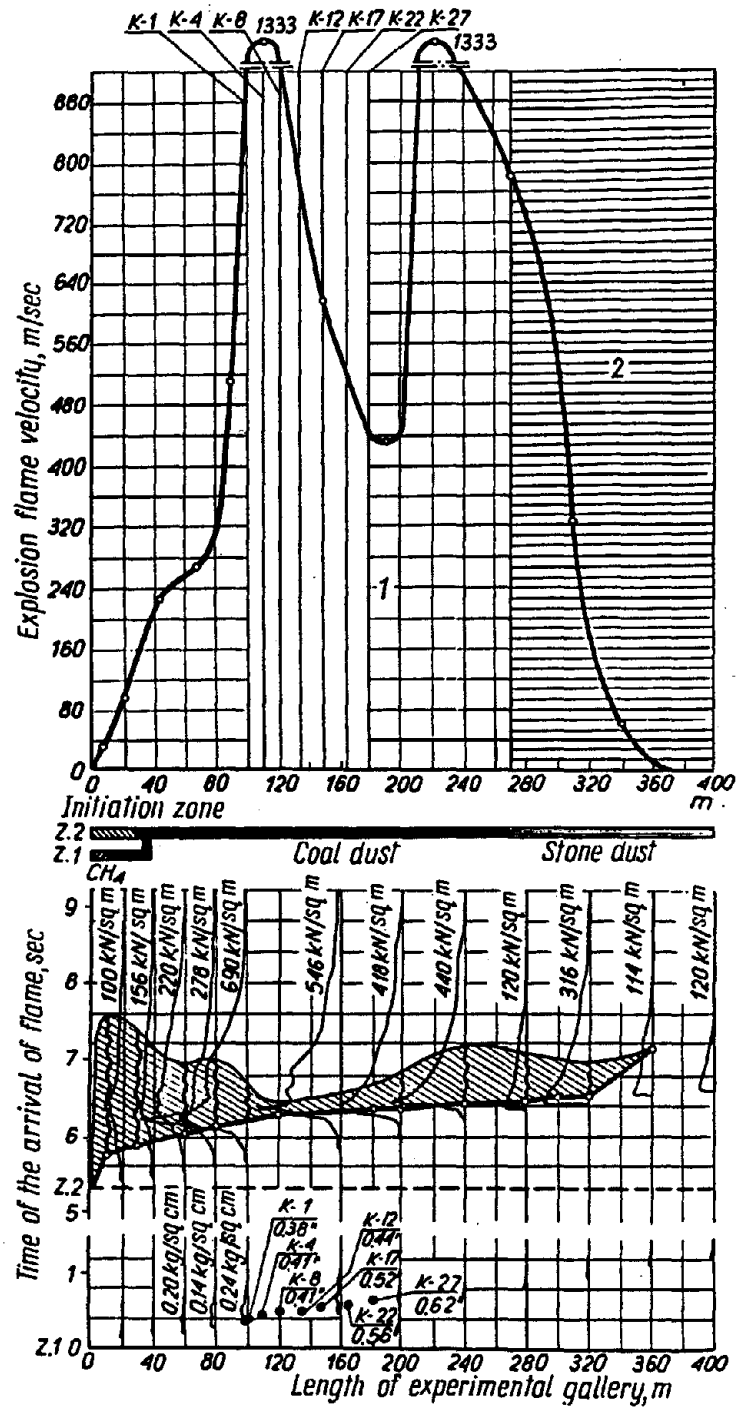


Fig. 9.51. A diagram of explosion No. 506 of the *d*85 coal dust, $n = 50\%$; investigations on the dependence $Q_{II} = f(t_p)$; coal dust explosion initiator 30mPII (Z.2 initiator 2); the putting of barriers into action by the explosion of 50 cu m CH_4 9.5% (Z.1 initiator 1) in the parallel gallery; *1* — from 100 to 180 m water barrier, 16 sets of containers at 3 m distances, $Q = 405$ kg/sq m; $t_p = 5.68$ sec; *2* — stone dust protecting zone, $Q = 2.75$ kg/sq m. Explanation of symbols: *K-1*, *K-4*, etc. mean first, fourth, etc. trough; numbers under these symbols — time of putting a given trough into action.

4 sec in the case of the straight line *1*, and when it exceeds 3 sec in the case of the straight line *2* — is not only lower than the effectiveness of stone dust barrier but becomes simply inadequate, since evan 400 kg of water per sq m will not stop an explosion. This is illustrated by the diagram of explosion No. 506 presented in Fig. 9.51. The water barrier $Q = 405$ kg/m did not stop this explosion, the value of t_p in this case having been equal to 5.68 sec.

The dependence of the effectiveness of water barriers upon the time in which they are put into action t_p, as shown in the diagram in Fig. 9.51, is well comparable with the analogous effectiveness of stone dust barriers shown in Fig. 9.28*b* and discussed in Section 9.1.11.8 because the mean flame velocities before the barriers were in both cases almost identical amounting to 345 ± 29 m/sec in the experiments with stone dust barriers, and to 350 ± 20 m/sec in the experiments with water barriers.

The fact that it had been impossible to achieve a stabilization of the effectiveness of water barriers with reference to the increase of the value of t_p can be explained as follows. Water very effectively stops a coal dust explosion when — at the moment of the arrival of the flame to the barrier — it is well dispersed in the gallery's cross section. However, if the flame reaches the zone of the barrier when water had already settled on the surface of the gallery, the effectiveness of the barrier diminishes. The results of the 32 tests of the effectiveness of water in stoping coal dust explosions are bound up with the above facts. Water cannot be raised to the air from the gallery's surface as easily as stone dust. Moreover the spraying with water of the surface of the working covered with dry coal dust does not deprive this dust of its dispersibility because the dust does not become saturated with water. Consequently a blast can easily raise this dust but water is not raised so easily and the result is that the explosion becomes propagated. This would not have happened if the barrier were placed in a wet working where coal dust is well saturated with water. The conclusion from the above is this that water barriers can be employed in various conditions, but always in wet workings in which coal dust is entirely nondispersible as the result of being saturated with water. A simillar principle has been advanced already when the spraying with water of mine workings was discussed (Section 8.6).

9.2.4. The effectiveness of water barriers as depending on conditions of the dispersion of water in the cross section of the gallery

9.2.4.1. General information. Basic investigations, similar to those described in Section 9.1.12, had been carried out in the *EM Barbara* on

the effectiveness of water barriers depending upon the dispersion of water in the gallery's cross section [56].

In view of the fact that these investigations have been described on the occasion of discussing stone dust barriers the subject matter of this section is restricted to the results of the investigations in question, and to the comparison of these results with the analogous results obtained in the tests made with stone dust barriers. Accordingly three magnitudes were taken into consideration with reference to the quantity of water and the distribution of water on the barrier:

Q — the quantity of water on the entire barrier per 1 sq m of the gallery's cross section, kg/sq m,

Q_1 — the quantity of water in one set of containers or in one container per 1 sq m of the gallery's cross section, kg/sq m,

Q_v — the concentration of water in the zone occupied by the barrier, kg/cu m.

The value of Q normally fixed by regulations, has already been indicated when the effectiveness of water barriers under diverse conditions has been considered in previous chapters.

Investigations concerning the influence of Q_1 and Q_v upon the effectiveness of water barriers were carried out in the explosion conditions analogous to those procured for the tests with stone dust barriers described in Section 9.1.12. In the investigations now discussed water containers of

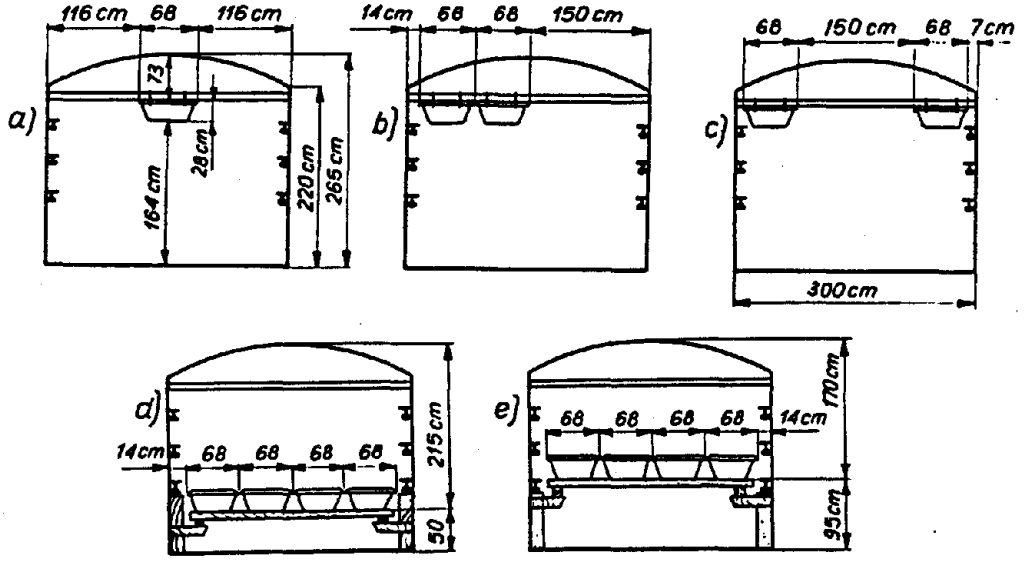


Fig. 9.52. The ways in which water containers were placed in the 400 m experimental gallery of the cross section area equal to 7.5 sq m.

brittle polysthyrene were used, their form being that of a truncated pyramid the bases of which measured 60×40.5 and 60×21 cm, respectively, the depth of the container being equal to 28 cm. Eeach container held 37.5 kg of water. The edges of the containers were rounded so as to allow their being suspended from roof bars. The investigations were carried out in the 400 m gallery of a cross section area measuring 7.5 sq m.

The ways in which containers were placed in the experimental gallery are shown in Fig. 9.52*a*, *b*, *c*, *d*, *e*.

9.2.4.2. The influence of the value of Q_1 on the effectiveness of water barriers. In the tests of water barriers described in previous chapters the values of Q_1 oscillated from 15 to 24 kg/sq m.

When the influence of the value of Q upon the effectiveness of water barriers was investigated it has been found that the reduction of the value of Q_1 to 5 kg/sq m diminishes perceptibly the effectiveness of the barriers. In other words for stopping an explosion higher values of Q_1 are necessary than 5 kg/sq m.

It should be concluded from the above that the value of Q_1 in practice never ought to be less than 10 kg/sq m with water containers placed symmetrically since such had been their distribution during the investigations.

The results of these investigations justify still another conclusion, namely, that in galleries of larger cross section areas than 7.5 sq m water will be also dispersed effectively provided, of course, that the number of containers used will be appropriate for the given width of the gallery.

In the course of analogous investigations on stone dust barriers it has been established (Section 9.1 12.2) that the reduction of the value of Q_1 to 2.1 kg/sq m had not yet lowered the effectiveness of barriers. This difference speaks in favor of the effectiveness of dispersing stone dust at reduced values of Q_1.

As an illustration of this series of experiments in Fig. 9.53*a* a diagram is shown of explosion No. 961 stopped by a barrier consisting of 28 single containers placed at the distance of 160 m from the gallery's face; Q = = 140 kg/sq m, Q_1 = 0.5 kg/sq m, Q_v = 5 kg/cu m.

9.2.4.3. The influence of the value of Q_v on the effectiveness of water barriers. The relevant investigations have shown that the value of Q_v can be reduced considerably without perceptibly diminishing the effectiveness of the water barrier on the condition that containers will be distributed symmetrically in the upper part of the gallery's cross section. The $Q_{v\,min}$ = = 0.25 kg/cu m was found. It is very interesting that for stone dust barriers, in the same conditions, the corresponding value of Q_v had been found of the same order of magnitude. Yet such a reduction of the Q_v value is not recommended. In Fig. 9.53*b* a diagram is shown of explosion

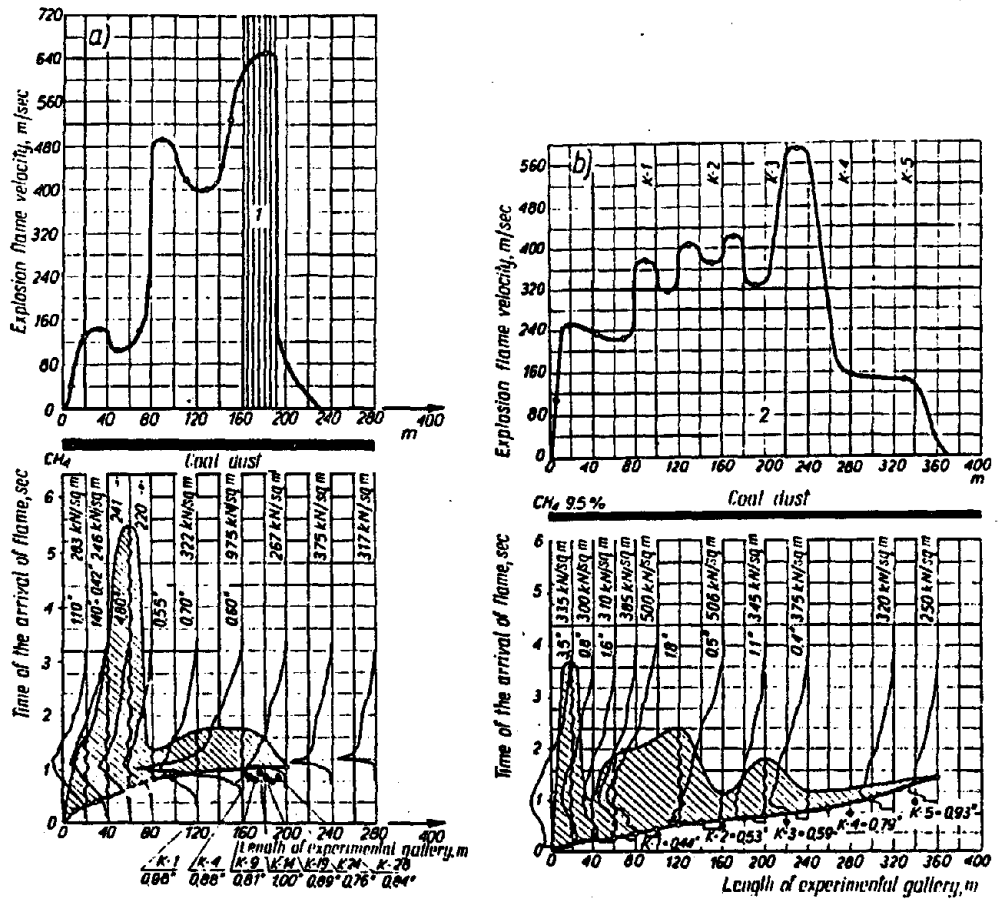


Fig. 9.53. Diagram of explosions: *a* — explosion No. 961 of the d25 natural coal dust, n = 18.4%, initiator 50 cu m CH_4 (9.5%), ignition 700 g of gunpowder; *1* — from 161 to 188 m water barrier of 28 single containers at 1 m distance, Q — 140 kg/sq m, Q_1 = = 5 kg/sq m, Q_v = 5 kg/cu m, t_p = 0.14 sec; *b* — explosion No. 1025 of the *d*25 natural coal dust, n = 16.8%, initiator 50 cu m CH_4 (9.5%), ignition 750 g of gunpowder; *2* — from 100 to 275 m water barrier of 5 sets of containers at 60 m distances, Q = = 23 kg/sq m, Q_1 = 5 kg/sq m, Q_v = 0.08 kg/cu m, t_p = 0.17 sec. Symbols as in Fig. 9.51.

No. 1025 in which the value of Q_v = 0.08 kg/cu m had been unusually low. Five single containers were distributed symmetrically at distances as long as 60 m; Q = 25 kg/sq m, Q_1 = 5 kg/sq m. The containers had been suspended under the roof bars. Under such unusual conditions the barrier stopped the explosion not earlier than at the distance of 370 m from the face of the gallery. The diagram presented in Fig. 9.53*b* is rather exceptional considering that the distances between the containers had been unusually long. Yet, even when the distance between the containers has

been 20 m explosions were now and again propagated with $Q_v = 0.1$ kg/cu m and $Q_1 = 2.1$ kg/sq m.

9.2.4.4. Distributed water barriers. The results of investigations, described in Section 9.2.4.3, are strictly connected with distributed barriers the aim of which has been discussed with reference to stone dust barriers in Section 9.1.12.3. In connection with investigations on the minimum values of Q_v very thorough tests were carried out of distributed barriers. These tests were of both fundamental and practical importance. Although, in accordance with the results presented in Section 9.2.4.3, the value of $Q_{v\,min}$ amounts to 0.25 kg/cu m, yet it has been agreed that Q_v in the case of water barriers should not amount to less than 1 kg/cu m. This is the same limit value as the one recommended in the case of stone dust distributed barriers.

The necessity of increasing the value of $Q_{v\,min}$ by so much, in comparison with the corresponding value established experimentally, is explained by the fact that the relevant experiments were carried out only in experimental galleries of 7.5 sq m or 5 sq m cross section areas, but it was not possible to make the tests in galleries of larger cross section areas. When, therefore, the $Q_{v\,min}$ was being determined for practical purposes it had been necessary to allow a large factor of safety. Besides, in spite of the wide range of various coal dust explosions procured, and their initiators employed in the relevant experiments, the multiplicity of the possible characteristics of coal dust explosions could not have been exhausted.

When using distributed barriers the value of t_p increases gradually for the consecutive sets of containers. As the result, for a certain consecutive set, the value of t_p is the optimal value — that is, the most advantageous value from the viewpoint of the barrier's effectiveness.

Distributed water barriers ought to be used only in places where dust is at least humid, analogously to conditions in which ordinary water barriers are used. If the coal dust is wet one may — in exceptional cases — apply a wider spacing between the sets of containers down to the value of $Q_v = 0.5$ kg/cu m. Distributed water barriers are employed instead of the spraying of coal dust with water. They have the same merits and the same faults as distributed barriers of stone dust.

Distributed water barriers cannot be used instead of the ordinary water barriers, just as distributed stone dust barriers cannot be used in the place of ordinary stone dust barriers. The length of the gallery's section occupied by an ordinary water barrier depends upon the typical support used in the gallery, upon the cross section number of the gallery according to the standard specification, and upon the distance between the separate sets of containers. With this distance equal to 2 m, for galleries in which yieldable arches are used and for the barrier with $Q =$

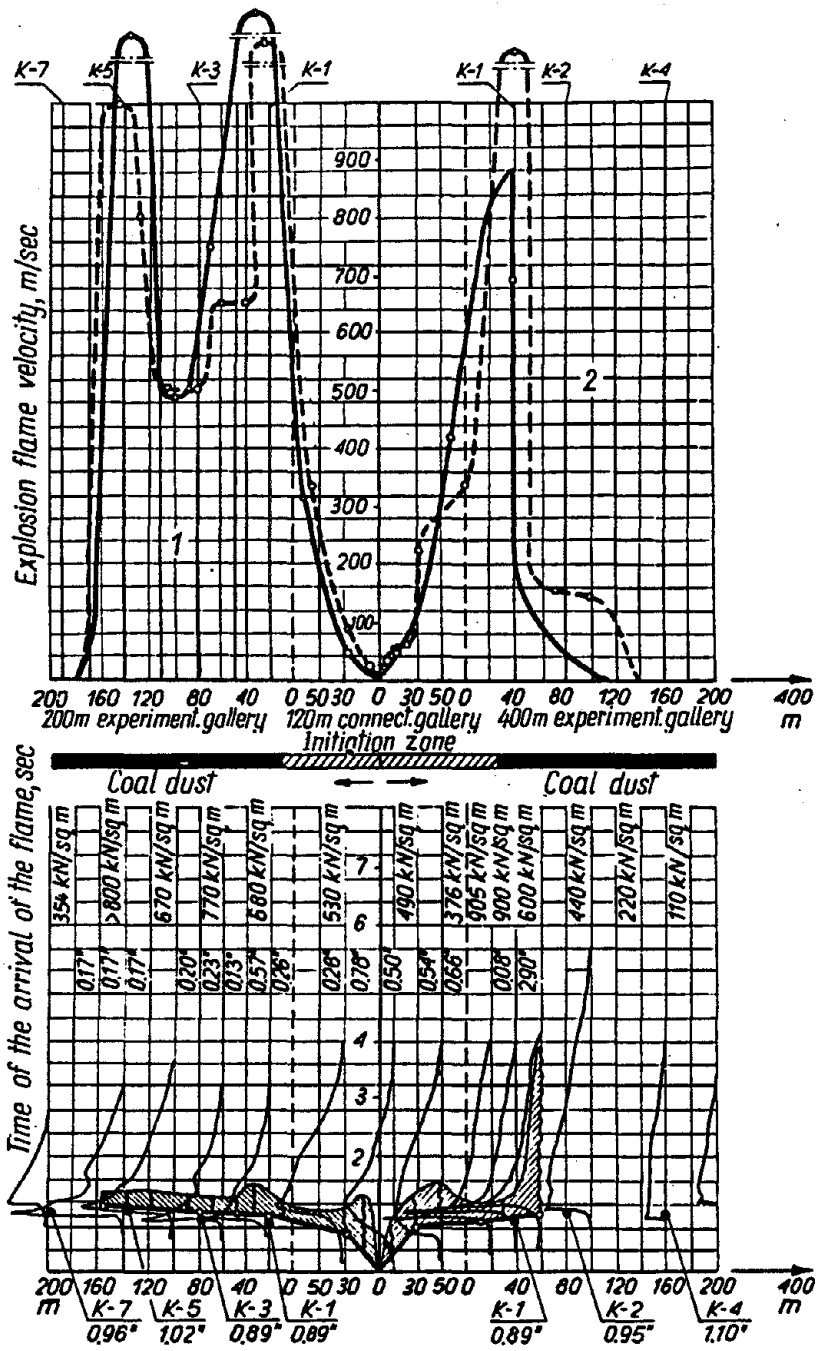


Fig. 9.54. A diagram of two-directional explosion No. 1154 of the d85 coal dust, $n = 60\%$, initiator at the middle of the connecting gallery, distributed water barriers: in the 400 m gallery at 40 m distances, $Q_v = 42$ kg/cu m; in the 200 m gallery at 30 m distances, $Q_v = 0.58$ kg/cu m; *1* — from 20 to 180 m water barrier of 7 sets of 2 containers each at 30 m distances, $Q = 105$ kg/sq m; *2* — from 40 to 380 m water barrier of 10 sets of 3 containers each at 40 m distances, $Q = 150$ kg/sq m. Symbols as in Fig. 9.51.

= 200 kg/sq m, the length of the barrier zone oscillates between 16 and 30 m for cross section numbers from 1 to 10. The number of containers in a set amounts to from 3 to 6.

When using distributed water barriers with Q_v = 1 kg/cu m the distances between the sets of containers vary from about 23 to about 13 m. With Q_v = 0.5 kg/cu m these distances obviously are twice as long.

For galleries with timber rectangular support, depending on the cross section number from 2 to 15, the length of the zone of an ordinary water barrier amounts to from 14 to 20 m, with distances between the sets of containers equal to 2 m.

In the cases in which distributed water barriers are used, with the value of Q_v = 1 kg/cu m, the distances between the sets of containers amount to from about 13 to about 19 m. For the given cross section of the working, assuming that Q_v = 1 kg/cu m, the distance between the elements of the barrier depends solely on the value of Q_1 and is approximately equal to the magnitude of that value.

The number of containers in a set varies from 2 to 6. In determining the number of containers in a set the available breadth of the gallery's cross section in its upper part had been taken into account.

The zones in which ordinary water barriers are located ought to be sprayed with water often enough in order to maintain a high degree of the saturation of coal dust with water. Of course, with distributed water barriers there is no need of spraying the zone with water since the assumption is exactly that such barriers are used instead of spraying with water. At any rate the working has to be kept permanently in a humid condition.

The effectiveness of distributed water barriers has also been examined in the *EM Barbara* with reference to the two-directional development of explosions [60]. In Fig. 9.54, by way of an example, a diagram of the single explosion No. 1154 is presented. This explosion, in spite of its violence, had been stopped by distributed water barriers in both the 200 and the 400 m galleries; Q_v amounted to about 0.5 kg/cu m and the distances between the sets of containers — to 30 and 40 m, respectively. The three zero points on the axes of abscissae denote: the point at which the explosion was initiated, and the faces of the 200 and 400 m galleries.

9.2.4.5. The effectiveness of water barriers placed unsymmetrically in the cross section of a gallery. Side barriers. The question of the unsymmetrical location of water containers in the gallery's cross section is one of a considerable practical importance on account of the traffic difficulties caused by the building in of barriers. Investigations were carried out on this subject analogous to those which concerned stone dust barriers (Section 9.1.12.4).

Locating water containers in one half only of the gallery's cross section (Fig. 9.52*b*) it was established that the lateral dispersion of water, from a distance of 150 cm from the sidewall, can be ineffective in cases of strong explosions even if the quantity of water on the barrier conforms to regulation requirements for nonmethane seams. By comparing the above results with those obtained in examining stone dust barriers one finds that the dispersion of stone dust in such conditions is more effective than the dispersion of water.

In accordance with the findings referred to above whenever it is necessary to leave a free passage to men by the side of the barrier the space free from containers should be reduced to the minimum in no case exceeding 1 m in width.

It was found that if single water containers are placed close to both sidewalls of a gallery (Fig. 9.52*c*) the effectiveness of the barrier is not reduced with the growth of the distance between these containers up to 150 cm.

From these investigations the conclusion can be drawn that when there are difficulties in locating water containers throughout the entire breadth of the gallery these containers can be placed near the sidewalls leaving a space between the containers not in excess of 150 cm in width.

9.2.4.6. The influence of lowering the location of water containers on the effectiveness of barriers. The effectiveness has been investigated of the dispersion of water from the barriers in the direction of the roof. The tests were carried out with containers placed 170 and 215 cm below the highest point of the roof (Fig. 9.52*e* and *d*). It was found that even such unusual location of containers did not cause a reduction of the effectiveness of the water barriers in the conditions in which the tests were made [56].

The established fact of the effective dispersion of water in the direction of the roof permits to treat, with considerable tolerance, the building in of water barriers in such cases in which, locally, there is a lack of free space in the upper parts of workings. However, the distance between the water containers and the lining or the open roof should not exceed 100 cm. Naturally the all too low location of containers across the entire breadth of the gallery would have created considerable difficulties in the way of the traffic of miners. Therefore, in accoadance with the results of the investigations, the containers may be placed at varying levels depending on local conditions, for example, if air ducts are installed on one side of the gallery the containers can be located underneath them in order to assure the best use of the free space.

9.2.5. Stopping with water barriers of the weakest coal dust explosions initiated by the roof layers of firedamp

9.2.5.1. General information. Analogous investigations on stopping the weakest explosions with stone dust barriers have been discussed in Section 9.1.13.

To investigate the effectiveness of water barriers in connection with explosions producing the weakest possible blast is a task of a tremendous fundamental as well as practical importance.

Very thorough investigations, which had been conducted on the weakest possible coal dust explosions, have already been discussed in Section 9.1.13 as well as in Sections 5.2 and 5.3.

It has been stated there that, in special conditions, very mild coal dust explosions of low flame velocities, corresponding to the low deflagration of coal dust, can develop even over long routes, for example, over 400 m as it has been established experimentally in the *EM Barbara*. Figures 9.43 and 9.44 contain illustration of such explosions. Explosions characterized by such an absence of variety in their development over long distance occur rather seldom. Much more frequently, however, such development occurs in the initial stage of explosions initiated by relatively mild combustion of methane causing a very weak blast. The dependence of the dynamic pressure, created by such explosions, upon the velocity of the flame has been discussed in Section 9.1.13.

When barriers are placed at a small distance from the gallery's face, for example, at a distance of 60 to 100 m it can easily happen that the blast which reaches the barrier will possess a very low dynamic pressure and this can have a decidedly negative influence on the effectiveness of the barrier.

The dust conditions, dependent on the quality of the coal dust and on the distribution of this dust, can be distinctly more dangerous beyond the barrier. Thus, having passed the barrier, the flame of the explosion can easily develop into an explosion even of a very violent kind. It should be stressed that in practice such a variability of the dust conditions occurs quite frequently. Reference to such conditions has been made in Section 9.1.13.

In conclusion it can be claimed that investigations on the effectiveness of water barriers, under conditions of the weakest possible explosions, are as tremendously important as those concerning stone dust barriers discussed in Section 9.1.13.

9.2.5.2. The problem of the effectiveness of water barriers consisting of rigidly fixed containers. In accordance with the remarks contained in Sections 9.2.1 and 9.2.2 it became necessary to verify the likelihood of

rigidly fixed water containers being destroyed before the arrival of the flame during particularly weak explosions. In view of the basic importance of this question many investigations were devoted to it in the *EM Barbara*. The investigations in question were carried out in conditions of the weakest possible explosions, initiated by the roof layers of methane, in much the same manner as investigations concerning stone dust barriers described in Section 9.1. Water containers of the following three types were used:

— of the Polish type made from polystyrene measuring: 60×32, 48×21; depth 28 cm and capacity 37.5 cu dec,

— of the Federal Republic of Germany type of polyvinyl chloride measuring: 75×50, 68×42; depth 27 cm and capacity 80 cu dec,

— of the Federal Republic of Germany type of foamed styrene F224 measuring: 72.5×47, 63.5×37.5; depth 30 cm and capacity 80 cu dec.

The containers were rigidly fixed beneath the roof bars or placed in framelike holders. The distances between the barriers and the gallery's face varied between 80 and 200 m. Dynamic pressures capable of putting the containers into action were given in Table 9.2.

It was found that the German made containers of polyvinyl chloride and of foamed styrene did not behave alike. The last named containers were more fragile and, therefore, they were damaged more easily before the arrival of the flame. This happened in about 80 percent of cases. In 20 percent of cases these containers had not been damaged before the arrival of the flame. The polyvinyl chloride containers were damaged in about 40 percent of cases after the passage of the flame; they were put out of shape through the action of the flame in about 30 percent of cases; and in 30 percent of cases these containers remained altogether undamaged.

This can be summed up by stating that in no cases the polyvinyl chloride containers functioned properly before the arrival of the flame. Generally in about 55 percent of experiments the barriers manufactured in the Federal Republic of Germany did not stop explosions. The fact that in about 45 percent of experiments the flame of the explosion faded away, either within the zone of the barrier or within a short distance beyond the barrier, has often been the result of the flame fading away without any stunting influence of water either because the explosion had been very weak, and unable to develop further, or due to the action of water after the front of the flame passed through the barrier. For, after all, in the case of very weak explosions, water poured out behind the front of the flame does play a part in reducing the ability of the explosion to develop. It should be remembered that the duration of the flame in very weak explosions is usually a few seconds.

In Fig. 9.55*a* a diagram is shown of explosion No. 1240 in which the

Federal Republic of Germany containers of polyvinyl chloride remained intact until the arrival of the flame and, in consequence, the barrier did not stop the explosion. Although the quantity of water on the barrier had been relatively small ($Q = 64$ kg/sq m) yet even a larger number of the sets of water containers would not have altered the result since all of them remained undamaged prior to the arrival of the flame.

Polish containers behaved in a distinctly different manner although, being rigidly fixed, in about 50 percent of cases their functioning did not conform to the basic requirements — that is, the containers were not damaged before the arrival of the flame. Namely, in approximately 50 percent of cases Polish containers were damaged before the arrival of the flame; in about 10 percent of cases they were damaged with a delay — that is, after the passage of the flame; in about 25 percent of cases the containers were put out of shape through the direct action of the flame; and in about 15 percent they remained intact before the arrival of the flame. In other words: in about 50 percent of cases the containers were either damaged with a delay, or put out of shape through the action of the fire, or they remained altogether intact.

Generally the effectiveness of water barriers composed of Polish containers was better than that of barriers with FRG containers, namely, the former did not stop explosions only in about 22 percent of experiments. These better results of tests should be ascribed to the distinctly lower capacity of Polish containers. This, in the face of a very weak explosion blast, had greatly improved the dispersion of water. As an illustration of this series of experiments a diagram is given in Fig. 9.55b of explosion No. 1248 not stopped by a water barrier, located at the distance of 60 m from the gallery's face, in spite of the fact that the containers had been damaged before the arrival of the flame — that is, water had been poured out from these containers. This experiment exemplifies the fact that, when containers are rigidly fixed, water cannot be dispersed well from them by very weak explosions even if the containers become damaged before the arrival of the flame.

In Fig. 9.55c a diagram is presented of explosion No. 1337 stopped by a water barrier of 6 three-container sets of Polish containers; $Q = 90$ kg/sq m; the containers had been damaged before the arrival of the flame. The fact that the quantity of water on the barrier was larger in this, than in the previously discussed, case contributed also to the stopping of the explosion.

The investigations described above proved that in numerous cases of very weak explosions the blast does not destroy the water containers and, in consequence, the barrier cannot serve its purpose.

The ineffectiveness of water barriers consisting of rigidly fixed con-

tainers, as discussed here, refers to cases of particularly weak explosions. When explosions are stronger the rigidly fixed containers act properly since they become destroyed before the arrival of the flame and, therefore, the blast disperses the water instantaneously. This has been very clearly confirmed in the course of a great number of experiments.

It is generally understood that barriers ought to be effective in the entire broad range of conditions, created by all possible kinds of coal dust

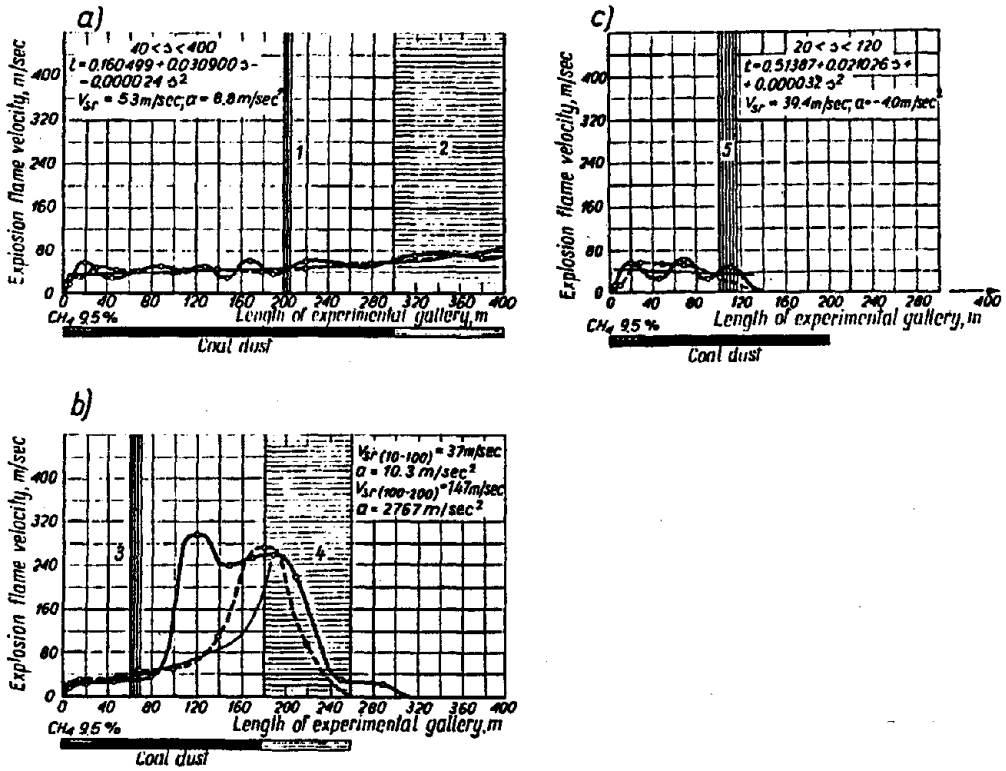


Fig. 9.55. Diagrams of explosions: *a* — explosion No. 1240 of the *d*25 natural coal dust, $n = 20\%$, initiator: a roof accumulation of methane 9.5% CH_4, $V_M = 4$ cu m, $H = 12.2$ cm, $L = 30$ m; *1* — water barrier of FRG polyvinyl chloride containers, 3 two-container sets each at 3 m distances, $Q = 64$ kg/sq m; containers untouched until the arrival of the flame; *2* — stone dusted protecting zone, $Q = 275$ kg/sq m; *b* — explosion No. 1248 of the *d*25 natural coal dust, $n = 19.5\%$, initiator: a roof accumulation of methane 9.5% CH_4, $V_M = 4$ cu m, $H = 12.2$ cm, $L = 30$ m; *3* — water barrier of Polish polystyrene containers, 4 three-container sets each at 3 m distances, $Q = 60$ kg/sq m; containers damaged prior to the arrival of the flame; *4* — stone dusted protecting zone, $Q = 220$ kg/sq m; *c* — explosion No. 1337 of the *d*25 natural coal dust, $n = 20\%$, initiator: a roof accumulation of methane 9.5% CH_4; *5* — water barrier of Polish polystyrene containers, 6 three-container sets each at 3 m distances, $Q = 90$ kg/sq m; containers damaged prior to the arrival of the flame.

explosions in mines, since it is difficult to foresee what kind of explosions the barriers will have to deal with.

In Polish mines, taking into consideration the results of previous investigations as well as the results of investigations discussed in this chapter, the use of water barriers is recommended in humid or wet workings in which dry, dispersible coal dust cannot be found at all.

In such workings the spraying of the surface with water is also recommended since stone dusting cannot be as effective because the dust very rapidly loses its dispersibility.

The weakest coal dust explosions achieved in the experiments described here are possible in the presence of dry, dispersible coal dust, an explosion of which can be initiated by a very weak initiator. An explosion of humid or wet coal dust cannot be at all weak as has been demonstrated in the course of very extensive investigations in the *EM Barbara*. To start an explosion of such dust a very strong initiator has to be used. Consequently, the propagation of the explosion of this dust is possible only in the presence of a very strong blast preceding the flame. In such conditions water barriers of rigidly fixed containers would function properly, no doubt, provided that the time of putting the containers into action is not too long — that is, if the time interval between the arrival to the barrier of the blast and the moment of the arrival to the barrier of the front of the flame is not too long. The conclusion is that barriers with rigidly fixed containers can be used in workings in which only humid or wet coal dust is present.

9.2.5.3. The effectiveness of water barriers composed of loosely placed containers. In view of the defective functioning of rigidly fastened water containers investigations were carried out on the effectiveness of water barriers composed of containers loosely placed on immovable supports, or on frames used in barriers of the *EM Barbara* type shown in Fig. 9.45. The minimum dynamic pressures which suffice to put into action the containers which are so placed are given in Table 9.2.

Investigations on the effectiveness of such containers in a very wide range of explosions were discussed in Section 9.2.3. However, these investigations did not include the weakest explosions of coal dust produced for the experiments discussed in Section 9.2.5.2. It was necessary, therefore, to carry out investigations on the effectiveness of barriers composed of loosely placed containers under conditions of exactly such weakest coal dust explosions.

In these tests containers had been placed at distances of from 60 to 100 m from the face of the gallery. The majority of tests were made with the use of containers made in Poland; yet containers received from the *EM Tremonia* had also been used. In all the cases in which the flame had

reached the location of the barrier the containers were put into action in contrast to rigidly fixed containers.

When containers had been located lengthwise in the gallery — that is, the shorter side turned in the direction of the gallery's face it did happen occasionally that they were not put into action. Therefore, this way of placing them should be avoided. The containers manufactured in the Federal Republic of Germany, placed loosely, were less effective than Polish made containers — that is to say in two tests out of six they did not stop the explosion. This was caused by the too large capacity of these containers. Containers made of the foamed styrene proved to be distinctly superior to the polyvinyl chloride containers.

In Fig. 9.56*a* a diagram is shown of explosion No. 1355 not stopped by a barrier of FRG made containers. The mean velocity of the flame before the barrier amounted to $V_{sr} = 51.8$ m/sec; the acceleration $a = -0.6$ m/sec^2; the dynamic pressure before the barrier amounted to 1.6 kN/sq m; the quantity of water on the barrier was small $Q = 85$ kg/sq m. To be effective this barrier should have had a much larger quantity of water since the explosion, after passing the barrier, developed with a considerable acceleration.

Polish containers, normally placed on bases and also on roof bars, stopped coal dust explosions quite well with quantities of water $Q = 120$ kg/sq m and $Q_v = 5.7$ kg/cu m. With smaller quantities of water Q, in two out of 10 experiments, water barriers did not stop the explosions; it was found that some of the containers had fallen off their bases with a delay.

In Fig. 9.56*b* a diagram is shown of explosion No. 1402 not stopped by a barrier composed of Polish containers with $Q = 105$ kg/sq m. This is a particularly good example of an explosion developing with an almost uniform velocity. The mean velocity of the flame amounted to 46 m/sec, acceleration $a = 3.6$ m/sec^2, the dynamic pressure before the barrier amounted to 1.0 kN/sq m. The explosion in question, though not stopped by the barrier within a small distance, faded away, nevertheless, at the distance of about 120 m beyond the barrier. However if a more dangerous coal dust had been present beyond the barrier the explosion could have developed there. It was just in this explosion that some of the containers had fallen off their rests behind the front of the flame. In any case, the passing through this barrier of a very weak explosion is a very characteristic fact. It can be surmised that, if the quantity of water on the barrier corresponded to the regulation requirements — that is, if it were approximately twice as large as had actually been used, the explosion would have been stopped since undoubtedly a larger number of containers would have been put into action at the right time.

The above examples represent the most difficult stoppage of an explosion by a distributed barrier; in other cases such barriers stopped explosions within a much shorter distance.

Investigations were also carried out on the effectiveness of distributed water barriers. These investigations indicated that even with distances between the sets of containers amounting to 30 m, with $Q_v = 0.6$ kg/cu m and $Q = 90$ kg/sq m, explosions have been frequently stopped by two sets of containers.

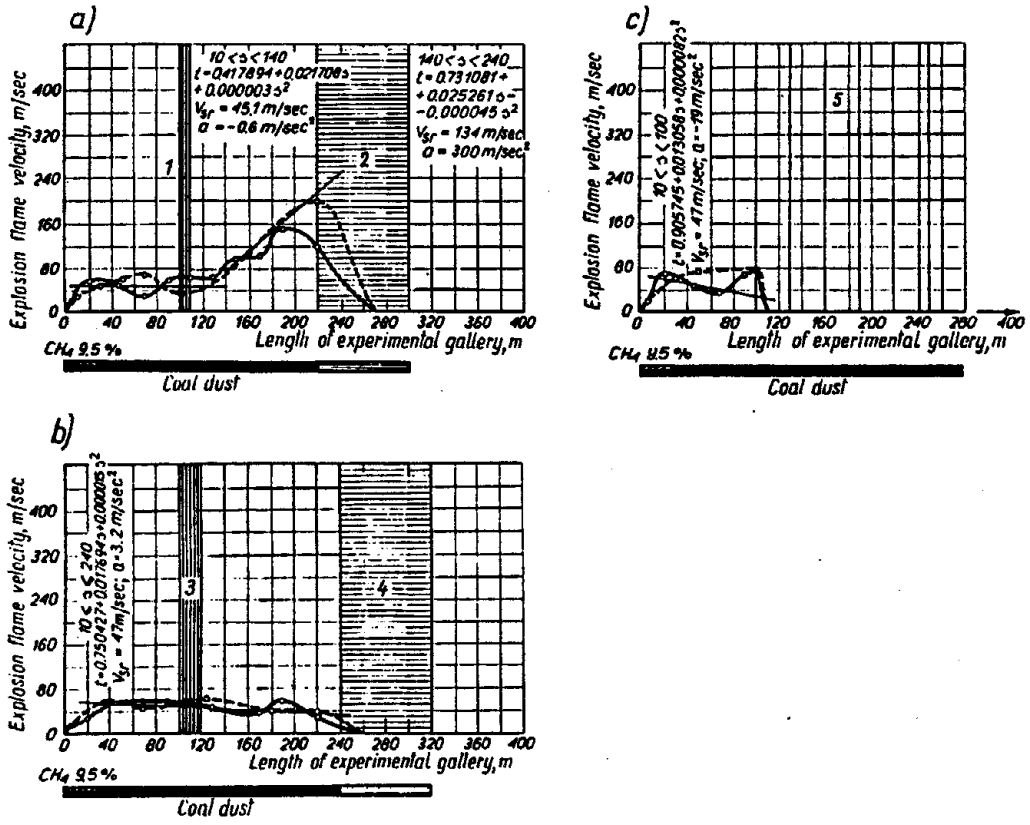


Fig 9.56. Diagrams of explosions: *a* — explosion No. 1355 of the *d*25 natural coal dust, $n = 20\%$, initiator: a roof accumulation of CH_4 9.5%; *1* — water barrier of FRG containers, 4 two-container sets each at 3 m distances, $Q = 85.3$ kg/sq m, $Q_v = 9.5$ kg/cu m; *2* — protecting zone covered with limestone dust, $Q = 220$ kg/sq m; *b* — explosion No. 1402 of the *d*25 natural coal dust, $n = 20\%$, initiator: a roof accumulation of CH_4 9.5%; *3* — water barrier of Polish polystyrene containers, 7 three-container sets each at 3 m distances, $Q = 105$ kg/cu m, $Q_v = 5.8$ kg/cu m; *4* — stone dusted protecting zone, $Q = 220$ kg/sq m; c — explosion No. 1414 of the *d*25 natural coal dust, $n = 20\%$, initiator: a roof accumulation of CH_4 9.5%; *5* — distributed water barrier of Polish polystyrene containers, 6 three-container sets each at 30 m distances, $Q = 90$ kg/sq m, $Q_v = 0.6$ kg/cu m.

In Fig. 9.56c a diagram is given of explosion No. 1414 which was stopped by a distributed barrier on the spot. The mean flame velocity before the barrier amounted to about 47 m/sec, the dynamic pressure to 6.4 kN/sq m.

Generally it should be stated that water containers, placed loosely on frames, brackets or roof bars, stop very weak explosions but the quantity of water required in such cases has to be larger than in the cases of stronger explosions because water is not dispersed well enough by the weak blast of very weak explosions.

Anyhow, the above mentioned two cases of explosions that were not stopped occurred because the quantity of water on the barrier had been too small. With the quantity of water $Q = 200$ kg/sq m — that is, half of the quantity required by regulations for methane seams, one can rely on stopping an explosion.

Distributed barriers with $Q_v = 1$ kg/cu m are very effective and can be recommended also since in explosions of the type discussed here they had been effective even with $Q_v = 0.6$ kg/cu m.

But of course containers should in no case be placed lengthwise — that is, with the shorter side directed toward the gallery's face since the barriers are distinctly less effective when the containers are so placed.

9.2.5.4. The effectiveness of side barriers. On account of the difficulties brought to light in connection with stopping particularly weak explosions by water barriers investigations were carried out also on the effectiveness of side barriers under the same conditions.

It was found that in order to stop explosions water containers had to be located so as to occupy at least one half of the gallery's cross section — that is, over a section of 150 cm counting from one of the sidewalls. Two containers had been placed on a base. In this way the other half of the gallery's cross section remained free for the passage of men and for locating air ducts or other conduits. The quantity of water necessary for stopping explosions amounted to $Q = 150$ kg/sq m.

Referring to the findings given in Section 9.2.4.5 in which analogous investigations were discussed on stronger explosions it should be remembered that, under the conditions in which those investigations were conducted, the distance of 150 cm between the containers and the sidewalls proved to be too long for the effective functioning of the barrier. However when the single containers had been placed on both sides of the gallery near the sidewalls, with the distance between the containers amounting to 150 cm, the barriers proved to function effectively when explosions were strong. In the cases of very weak coal dust explosions water containers arranged in the same way had been ineffective. It ought to be

mentioned, however, that in these investigations the quantity of 150 kg of water per 1 sq m had not been exceeded. With the quantities of water corresponding to regulations concerning methane seams it can be expected that such a distribution of containers would permit to stop explosions of a wide range of violence.

Stone dust side barriers occupying one half of the gallery's cross section, in conditions of very weak explosions, proved to possess the effectiveness analogous to that of water side barriers — that is, the stone dust side barriers could also be placed on one side of the gallery. The quantity of stone dust on the barrier Q sufficient to stop an explosion was the same as in the case of water side barriers placed on one side of the gallery (Q = 150 kg/sq m).

One should not forget that in the case of stronger explosions the lateral dispersion of stone dust had been more effective than that of water. Considering the results of investigations carried out under conditions of stronger explosion it can be concluded that water side barriers placed on one of the sides of a gallery may be used. But the distribution of containers ought to be avoided in which they occupy only half of the gallery's breadth. It is indicated that they occupy a part of the other half of the gallery's cross section leaving a free passage of not more that 100 cm. Of course the breadth of the part of the working left free of water containers depends on the cross section of the gallery and on its total breadth. The breadth of the part of the gallery indicated above, to be left free for the passage of men and for locating air ducts, represents a compromise and is a generalized solution in which an adequate safety margin is provided.

As it has been mentioned in Section 9.1.12.5 in the world coal industry the problem of protecting with barriers low and, at the same time, wide galleries has become a really very pressing problem. In the section referred to above investigations had been described that were carried out in the *EM Barbara* with side barriers about 200 cm distant from the sidewall. Unfortunately at the time of writing this book no such investigations were carried out with water barriers. In the *EM Tremonia* water barriers were tested in a gallery 450 cm wide, 150 cm high and 95 m long. These investigations, mentioned in Section 9.1.12.5, produced in general positive results but they were carried out under conditions of strong explosions. It is absolutely necessary to carry out analogous investigations in conditions of very weak explosions, initiated by roof accumulations of methane, because it is exactly in such conditions that the lateral dispersion of water may be found to be of little effect.

9.2.6. Foreign investigations concerning water barriers

In the *EM Tremonia* investigations were carried out on a large scale on water barriers. Comparative tests were also made of the effectiveness of water barriers and of stone dust barriers. The tests were carried out also in several inactive collieries. The results of these investigations were, on the whole, consistent with the Polish results.

Investigators in the Federal Republic of Germany agree with Polish investigators that the quantity of water on water barriers per 1 sq m of the working should be the same as the quantity of stone dust on stone dust barriers in the case of stone dust barriers according to regulation requirements in force up to date. As it is known this quantity is larger than the quantity sufficient for stopping explosions determined in the course of investigations. Of course the idea behind this is that a sufficient safety margin ought to be provided for the effectiveness of barriers. Investigators in the FRG compared water barriers with stone dust barriers of the *Dortmund* type. At very low velocities from 25 to 45 m/sec water barriers, as well as stone dust barriers, had fallen short of expectations. At higher flame velocities between 50 and 350 m/sec both types of barriers had been effective. At very high velocities, reaching the mark of 1000 m/sec, both types of barriers had fallen short of expectations — that is, they did not always stop explosions. It should be noted that containers used in the Federal Republic of Germany have capacities equal to 30, 50 or 80 cu dec.

The results of these tests did not agree with the results obtained in the *EM Barbara* particularly in what concerns very weak explosions which had been assuredly stopped by barriers of the *EM Barbara* type. At very great flame velocities the *EM Barbara* type of barriers had also stopped the explosions.

Very interesting were the results obtained by FRG investigators in galleries of the cross section area measuring 15 sq m. It was found that water barriers function effectively in such galleries also. Accordingly water barriers are admitted in the Federal Republic of Germany for an extensive use, the containers being rigidly fastened as a rule. Note that the rigid fastening of containers — at very low flame velocities — makes water barriers ineffective as was demonstrated in the course of Polish investigations.

In the Federal Republic of Germany no investigations were carried out on the influence of the time of putting barriers into operation upon their effectiveness. As previously stated in Section 9.2.3.3 it has been established, in the course of Polish investigations, that water barriers

fail to act effectively when the times of putting them into operation are prolonged.

Investigations carried out in the Federal Republic of Germany on the employment of distributed barriers led to the same conclusions as in Poland, namely, it is required that Q_v should not amount to less than 1 kg of water or stone dust per cubic meter in the zone in which the barrier is located. However, as can be judged from the publications dealing with this subject, there is a tendency in the FRG to replace distributed barriers by ordinary barriers. One can hardly agree with this point of view.

The position of the author of the present book has been explained in Sections 9.1.12.3 and 9.2.4.4.

Very interesting and penetrative investigations on barriers were, and still are, carried out at the Safety in Mines Research Establishment of the Ministry of Technology in Great Britain at *Buxton*.

The traditional British circumspection with regard to the introduction of any changes is worth mentioning here with appreciation. This applies also to the introduction of water barriers.

British investigators had stressed the fact that stone dust barriers, particularly such barriers of the *EM Barbara* type, so far had never failed. For instance, they did stop the potential great explosions at *Fenton* and *Mainsforth* in 1963. The results obtained in the course of British investigations are consistent with Polish results, especially with reference to conditions in which very weak explosions occur.

The French mining institute at *Cerchar* also conducts interesting research work though on a smaller scale.

About 60 years had passed since Taffanel's conception of employing barriers to stop coal dust explosions. During these years many investigations had been carried out on stone dust barriers, but the problem is still regarded as requiring further research work — a fact best evidenced by the animated activities in this field of the Safety in Mines Research Establishments.

9.2.7. A summary of investigations on the effectiveness of water barriers and concrete generalized recommendations

1. Normal water barriers — that is, those occupying a sufficient part of the gallery's width (at least 65 percent of the total width) are as effective as stone dust barriers in conditions of an explosion the flame velocity of which ranges from 100 to 700 m/sec.

2. The effectiveness of water barriers becomes insufficient when they are located just beyond galleries' bends or crossings. It is necessary, there-

fore, that they be located at a distance of not less than about 50 m from these bends or crossings.

3. Water barriers are ineffective when the time necessary to put them into action t_p is relatively long — over 3 sec. This can happen when the barrier is located at a rather considerable distance from the place of the initiation of the explosion — for example, at distance exceeding 500 m or when the net of workings, between the place at which the explosion was initiated and the barrier, is a complex one.

4. The rigid fastening of containers can ensure the effectiveness of water barriers when the explosions are sufficiently strong — that is, when the velocity of the flame amounts to not less than 100 m/sec; under such conditions the blast of the explosion will destroy a plastic container before the arrival of the flame.

5. In cases of particularly weak explosions rigidly fixed water containers could remain intact until the arrival of the flame; therefore, the rigid fastening of containers ought to be abstained from. The proper procedure is to place them simply on such frames as are used in barriers of the *EM Barbara* type.

6. In principle it is difficult to foresee whether in a given mine the possible coal dust explosions are likely to be of a very weak, or of a stronger kind. When the basic facts about coal dust explosions are known then, in some classical cases, it is possible to prognosticate that in certain workings an explosion cannot take a very mild course. Very mild explosions are possible, and very likely to happen, if a dry, rather dispersible, coal dust is present in the working. But in humid and, especially, in wet workings in which the entire coal dust is permeated by humidity an explosion can be started only by a strong intitiator and the explosion has to be violent to be capable of developing. In such cases the rigid fastening of containers would be quite acceptable. This information is worthy of being memorized because the rigid fastening of containers, for example, beneath the roof, to TH arches or to roof bars, is very advantageous under conditions prevailing in mines on account of the opportunity it affords of passing round pipings or other obstacles which make it difficult, or even impossible, to erect ordinary barriers that have to occupy at least 65 percent of the gallery's width. The effectiveness of barriers consisting of rigidly fastened containers would be raised very distinctly if the material from which the containers are manufactured could be made more fragile. It is possible that rigidly fixed containers, when improved that way, could act effectively even in cases of very weak explosions.

7. It ought to be underlined that all investigations on water barriers had been carried out practically in all cases with quantities of water Q per

square meter of the gallery's cross section considerably smaller than the quantities required by regulations. This was done for the purpose of ensuring a proper safety factor to the conclusions based on the findings. The tests were made in conditions representing a very wide range of degrees of the violence of explosions and the spraying with water of the zone, in which the barrier had been located, has been dispensed with although it is required by regulations. Naturally this was done also with the view to obtaining an as wide a margin of safety as possible.

Of particularly great importance are the results of investigations on the effective dispersion of water by water barriers in the cross section of the experimental gallery. These results are of considerable importance for the drawing of conclusions applicable to workings of larger cross section areas, and in connection with the problem of the unsymmetrical location of containers in workings a part of the cross section of which is occupied by air ducts, cables, etc. Actually the relevant tests established the fact that, especially in the case of very weak explosions, water is dispersed throughout the cross section of a gallery less effectively, when the containers are distributed unsymmetrically, than stone dust is under the same conditions. However if the galleries are only slightly broader than 3 m across, water barriers should be effective provided that the containers will be placed on either side of the gallery near the sidewalls, or beneath the roof along the axis of symmetry of the cross section of the working. The unit concentration of water Q_1 of a container set should be maintained, however, in such cases on the level of at least 10 kg/sq m. If these requirements are not fulfilled accurately it becomes necessary to compensate the default by keeping the zone of the barrier's location in a state of high humidity through spraying it with water. According to what was said previously water barriers ought to be used in wet, or at least humid, conditions.

The barriers should be placed in the upper part of the working. However, according to the results of tests concerning the dispersion of water during explosions, the distance up to 100 cm between the barriers and the lining or the roof is permissible.

When containers are placed symmetrically in the cross section of the working — that is, when the distances between the containers and the sidewalls are more or less equal on both sides, the quantity of water in a single set of containers (or even in a single container if the cross section area of the working is small) should not amount to less than 7.5 kg/sq m.

8. When the symmetrical location of water containers presents difficulties what are called side water barriers may be used leaving on one side of the working a passage not over 1 m in breadth.

At the present time no well based experimental findings are available

on the effectiveness of barriers located (erected) in exceptionally broad and relatively low galleries, in other words in galleries in which the proportion of the width to the height is rather uncommon. In such cases side barriers, located on both sides of the gallery, ought to be used or the containers should be placed beneath the roof, more or less at the center of the working, leaving passage room on both sides. All this on the condition, however, of having the unit concentration of water Q_1 amount to at least 10 kg/sq m.

9. When ordinary barriers are used the distances between the separate sets of containers ought to be from 2 to 3 m long. When there is not enough room the distances may be reduced, in the last resort, to 1 m.

10. Instead of spraying the workings with water, or in order to increase the safety factor, distributed water barriers may be used on the condition, however, that the volume concentration of water Q_v will not amount to less than 1 kg/cu m. Distributed barriers cannot be used as substitutes for ordinary barriers.

11. When the height of the working exceeds 4 m two stories of containers, one above the other, should be used always observing the rule that Q_1 should amount to at least 20 kg of water per square meter.

9.3. THE STRATEGY OF THE USE OF BARRIERS

9.3.1. General requirements

A proper distribution of barriers in a mine is of paramount importance. Therefore not only tremendous weight should be attached to the formal fulfilment of the regulation requirements but also a great care should be taken to locate the barriers with scrupulous attention to all local conditions, the details of which could not be taken into account in formulating the regulations.

Unfortunately cases are known in which a failure to place one particular barrier caused a great number of casualties.

According to Polish regulations the main and the auxiliary barriers are discerned. For both of these kinds of barriers the same quantity of stone dust or water is obligatory, namely, in nonmethane seams 200 kg of stone dust or water per square meter of the gallery's cross section area, and in methane seams — 400 kg/sq m.

The main barriers are used to isolate the ventilation regions; their erection is obligatory in all workings (even those that are inactive from the ventilation viewpoint) which connect the region with the rest of the mine. The ventilation dams constitute no obstacle that could stop the passage of an explosion. This applies also to dams built of bricks.

Anti-explosion dams, of course, can give a protection against the propagation of an explosion. These dams are suitably long sections of workings filled-in with sand, gypsum or other sufficiently airtight material. The thickness of the anti-explosion dam depends on the size of the cross section of the working. According to tests made in the *EM Barbara* [50] in workings of a cross section area measuring about 6 sq m dams made of bags of sand about 10 m thick, or gypsum dams about 4 m thick, are quite sufficient. They resist the pressure of a methane explosion of the magnitude of about 3.0 MN/sq m.

Auxiliary barriers are located (erected) inside the ventilation region. The basic binding principle is that in no case a coal dust explosion should be allowed to pass over a distance longer than 200 m without meeting a barrier on its way. This is, of course, the maximum distance between the place of the initiation of an explosion and the barrier. Efforts ought to be made to reduce materially this distance down to about 100 m. For with the increase of the distance, covered by a coal dust explosion, grow tremendously the consequences of it expressed in terms of the number of casualties.

Barriers should not be located nearer to the place at which explosions are likely to become initiated than 60 m. Only in exceptional cases this distance may be reduced to 40 m but then one has to accept the risk of the barrier failing to act effectively.

As places at which an explosion is likely to be initiated in nonmethane seams are regarded gallery faces where shotfiring operations are conducted, or workings with steady large accumulations of dangerous coal dust which cannot be protected by stone dusting or spraying with water on account of the fact that large quantities of the dust are accumulating steadily. This applies especially to inclined workings which serve as car haulage roadways or in which electric power cables are laid.

In methane seams as places of the possible initiation of an explosion are regarded also the places at which methane can accumulate or in which it was found to have already accumulated.

Apart from the above, in both methane and nonmethane seams, as the likely places for the initiation of a coal dust explosion are regarded fire fields not closed with anti-explosion dams.

9.3.2. Places at which barriers ought to be located

Barriers should be erected at such sections of galleries in which the cross sectional dimensions are as much as possible uniform not only in the zone occupied by the barrier but also in front of and behind this zone.

In no case a barrier ought to be located at a place where the cross section area of the gallery is larger nor, in particular, where the ripping of the roof had been done. The principle ought to be followed strictly that the shelves of the stone dust barriers, or water containers, may not be screened from the action of the explosion blast and must have an assured freedom to move under the impact of the blast.

It ought to be remembered that both stone dust and water barriers serve to stop coal dust explosions. They do not stop, unfortunately, methane explosions. Nevertheless they can also play a certain positive role in the case of a weak explosion of methane. Therefore, in no case should a barrier be placed beneath accumulations of methane behind the support, or at a place where firedamp fuses occur, if these fuses are connected with methane accumulations behind the support. In such cases the barrier might fail to stop a coal dust explosion, as the explosion of methane behind the support will be propagated beyond the zone of the barrier or a firedamp fuse can initiate an explosion of methane accumulated beyond the barrier's zone.

9.3.3. Detailed requirements concerning location of barriers in a ventilation region

9.3.3.1. General information. The purpose of auxiliary barriers is to isolate:

— the separate exploitation workings,

— the separate development headings in which explosives are employed, except in the case of headings shorter than 60 m driven from rock workings,

— the groups of workings ventilated by an independent interior air current,

— the active fire fields not protected by anti-explosion dams if a dangerous coal dust is present in the pertinent workings,

— the zones of considerable dustiness — that is, all such workings which, on account of being very dusty with coal dust, cannot be effectively stone dusted or sprayed with water.

Auxiliary barriers may also be located at 200 m distances over the entire length of workings which are very dusty and in this case ordinary barriers may be replaced by distributed barriers.

Apart from the above the employment of barriers is obligatory in methane seams:

— in headings driven without the use of explosives with the exception of headings shorter than 60 m driven from rock workings,

— at distance of 200 m in drift workings in which methane accumula-

tions occur of more than 1 percent, in workings with a separate ventilation and in drift workings in the "b" and "c" danger category through which the used air is carried away, if in these workings electric cables or other power conduits are laid.

Instead of erecting ordinary barriers at 200 m distances, distributed barriers may be used.

9.3.3.2. Divided barriers. If a gallery happens to be too short to have a barrier erected in it the barrier can be divided so that a part of it is located in the gallery, and the other part in the workings connected with this gallery.

Naturally in such cases the divided barrier has to contain — measured in every direction — the quantity of stone dust fixed by regulations as shown in Fig. 9.57. In the case of stone dust barriers the parts of the barrier not located in the gallery may be placed beginning from the point at which the gallery joins the other workings. In the case of water barriers, water containers ought to be located at the distance of 50 m from the junction of the gallery in question with other workings. At least one half of the water barrier should be situated in the gallery which is to be protected. If there is no room for that in the gallery, separate barriers must be erected in workings connected with the gallery as shown in Fig. 9.57*b*. In the case of stone dust barriers at least $^1/_4$ of the barrier must be situated in the gallery and then $^3/_4$ of the barrier will be erected in the workings connected with the gallery.

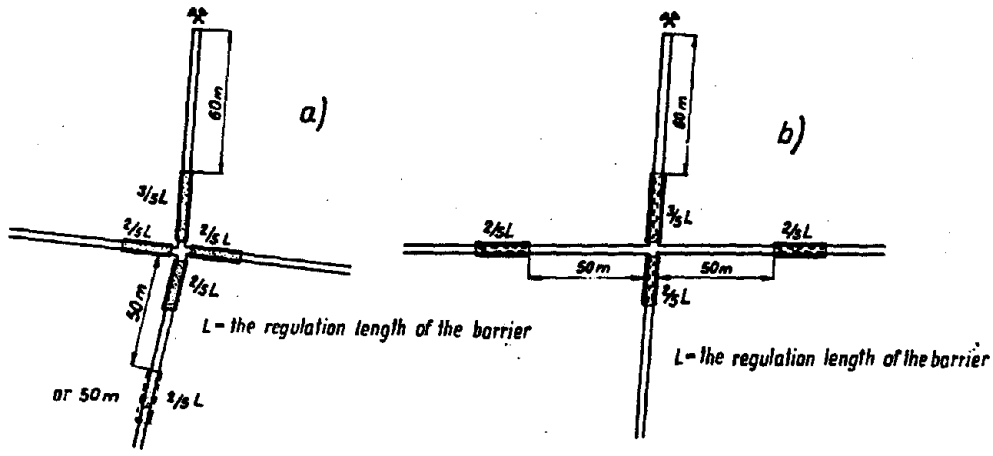


Fig. 9.57. Divided barriers: *a* — stone dust; *b* — water.

If the length of the gallery is too small to have a part of the divided barrier located there then, of course, the necessity arises of erecting

barriers in the workings connected with the gallery in question. The two gallery faces may be protected mutually by a barrier, if the location of the barrier between the galleries is possible without infringing the rule that the distance between the barrier and the gallery's face should not be less than 60 m. When this requirement is to be complied with, the distance between the two faces has to be at least 150 m in nonmethane seams. Obviously this distance must be greater in methane seams because the barrier has to be longer.

In the case of a serious explosion hazard in methane seams it may be permissible, by way of an exception, to reduce the distance between the barrier and the gallery's face to 40 m.

9.3.3.3. Difficulties connected with the use of barriers for isolating longwalls to which stepped-face system is adopted. In cases when the stepped-face system is adopted to two longwalls it is quite often possible to erect a barrier in the gallery situated between the two longwalls. But even if the distance between the longwalls permits of the erection of a barrier without transgressing the rules concerning the proper distance between this barrier and the longwall faces, the progress made at the longwalls makes it necessary to shift the barrier rather often. This is something difficult indeed to do. Therefore, in such cases it should be rather necessary to dust the gallery between the longwalls with stone dust, so as to bring the content of incombustible solid matter to 85 percent especially in methane seams. The employment of barriers in galleries running between the longwalls is possible practically only in such cases when the distance between the longwalls is so great that there is no necessity to shift the barriers frequently.

9.3.3.4. The protection of longwalls from the side of coal headings. It is exceedingly difficult to protect the longwalls from the side of the faces, longwall headings, the upper and the lower alike, driven in advance of the longwall. In most cases these headings are too short to permit of the erection of a barrier.

At the same time the initiation of an explosion is highly probable at the faces of such headings, especially in seams containing much methane. These headings, therefore, constitute a serious hazard for miners who work at the longwall where ordinarily dangerous pure coal dust is found. Consequently in coal headings, driven in advance of the longwall, the dusting with stone dust ought to be employed in methane seams as a means of bringing the content of incombustible solid matter in the mine dust up to 85 percent.

9.3.3.5. Typical examples of barrier locations. The typical locations of barriers are shown, by way of example, in Figs. from 9.57 to 9.61.

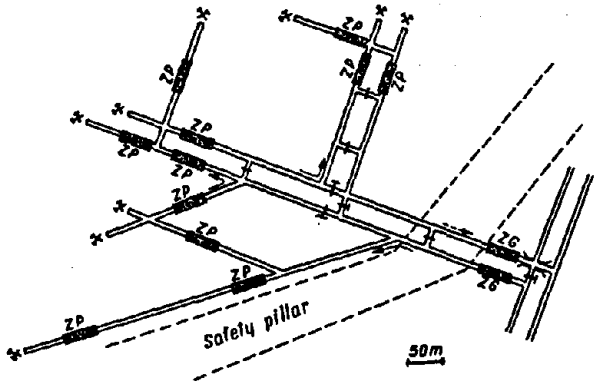


Fig. 9.58. The location of stone dust barriers in preparatory workings; methane seam of category III. *ZP* — auxiliary barrier; *ZG* — main barrier.

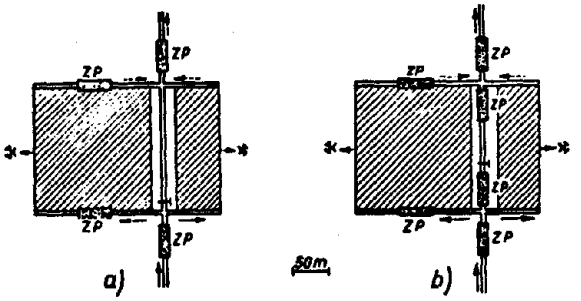


Fig. 9.59. The location of stone dust barriers isolating from each other two longwall workings. Symbols as in Fig. 9.58.

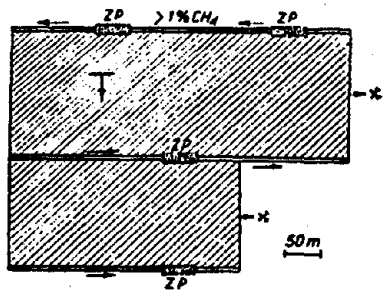


Fig. 9.60. The location of stone dust barriers or water barriers in the case of two longwalls with stepped-face system adopted; methane seam of category III. Symbols as in Fig. 9.58.

The discussion of the great variety of the nets of workings on the occasion of explaining the location of barriers would have taken a lot of space. For the location of barriers ought to be planned very carefully, separately for each individual case; approaching this task as if it were

a war game, the problem being that of stopping the attack of the enemy at as short a distance as possible from the place from which the attack began. The local conditions have to be considered as well as, naturally, the basic requirements and regulations. The principle on which the plans ought to be based is the one which requires that an explosion may not be allowed to pass a distance in excess of 200 m without encountering a barrier. Besides, all ventilation regions must be protected by main barriers from the remaining parts of the mine.

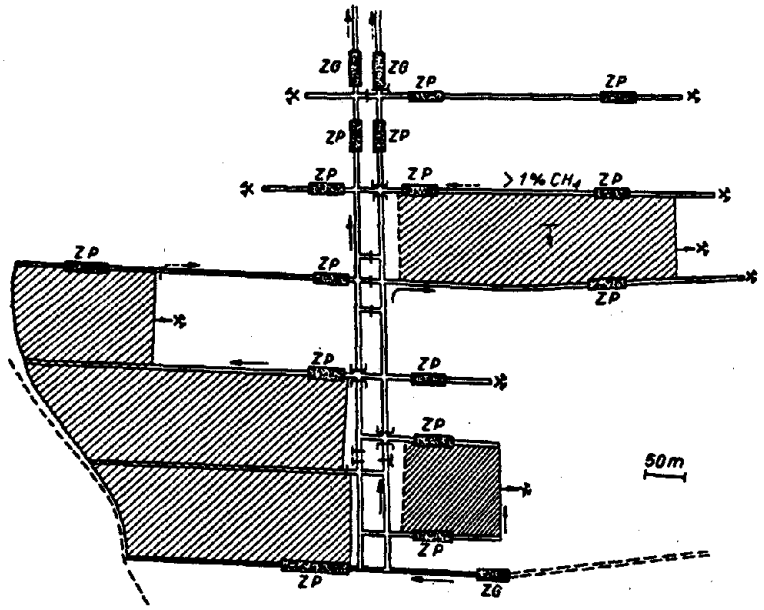


Fig. 9.61. The locations of stone dust barriers in a longwall system; methane seam of category III. Symbols as in Fig. 9.58.

Another rule to be observed is that barriers should be so located as to reduce, as much as possible, the necessity of shifting them with the progress of the work. Although it is a great advantage to the effectiveness of barriers when they are erected at the distance of about 100 m from the place of the probable initiation of an explosion yet, in practice this is possible in very rare cases. Locating a barrier at the above mentioned optimal distance from gallery faces, or from other places of the possible initiation of an explosion, would necessitate in many cases the shifting of the barrier and a much too frequent shifting at that. The obligatory distance between the barrier and the place of the start of the explosion (the initiation of the explosion) is from 60 to 200 m. In accordance with this when the gallery's face is moving toward the barrier the distance of

the newly erected barrier from the face should amount to 200 m. On the contrary, if the face moves away from the barrier it will be advantageous to erect the barrier at the distance of 60 m from the face. In order to simplify the denotation of the place at which the eventual explosion could be initiated such places are called, for short, the faces since it is at the faces that explosions are most frequently initiated.

In the examples given here the barriers are located in strict accordance with the above principle. Of course as the work progresses the distances between the barriers and the faces change accordingly.

In the figures discussed here the auxiliary barriers are denoted by the symbol *ZP* and the main barriers by the symbol *ZG*.

These figures are self-explanatory. They illustrate the principle that galleries in methane seams, ventilated with an auxiliary ventilation system, require barriers to be located at 200 m distances. In methane seams barriers have to be erected also in galleries which are actually not being driven. The protecting with barriers of inactive galleries in methane fields, even if the access of men to them is made impossible, is obligatory because an explosion of methane can be initiated also in the absence of the factors which are usually responsible for the ignition of methane.

In some of the figures explanations are given that the examples they present are of locations of stone dust barriers. Water barriers should be located quite analogously except that they ought not to be placed close beyond the crossings or the bends of galleries.

In Polish mines when the longwall system is employed single lower and upper headings are driven. If there is a greater number of such headings, parallel to each other, with normal crosscuts it becomes necessary, unquestionably, to increase the number of barriers which have to stop an explosion in each of the headings. It should be mentioned that in distinctly methane fields, particularly when the daily winnings from longwalls are large, the necessity arises to run at least two parallel air headings.

When the well known American *room and pillars* system is employed the use of barriers is connected with particular difficulties. In view of the fact, established in experience, that also with this system the use of barriers is necessary, research work is being done at the present time on the solution of the above rather difficult problem. In any case with this system it is necessary to employ safety measures against the initiation of a coal dust explosion through a local explosion of methane in the field behind the front of the work. To these measures belongs the wide use of methanometry with an automatic safety cutout switch especially at such places where electric appliances are not explosion proof, or where the connections with the power network are not protected at all.

9.3.4. The use of anti-explosion dams and of storied barriers

Anti-explosion dams. An ordinary dam, made of bricks, separating the used-up panels from the kept-up active workings does not suffice as a protection against the propagation of an explosion from the used-up panel. To this end it is necessary to use anti-explosion dam filled with stowing materials or with sand bags, about 10 m thick, or filled with gypsum and then its thickness may be smaller by 50 percent.

Storied barriers. In methane seams, in workings marked as containing methane accumulations close to 5% CH_4, storied barriers should be used.

Storied barriers ought to be so erected as to leave a passage to make the gallery's face accessible. The quantity of stone dust on storied barriers should amount to 600 kg per square meter of the gallery's cross section.

Storied barriers may be located inside of the marked zone or before that zone. The erection of storied barriers is not obligatory if the methane accumulations in the workings are liquidated during a single shift. However, when methane accumulations cannot be liquidated quickly the time in which it will be necessary to erect a storied barrier, counting from the moment in which it had been decided to mark the working, should be fixed by the mining authorities of the district.

9.4. TRIGGERED BARRIERS FOR STOPPING FIREDAMP AND COAL DUST EXPLOSIONS PARTICULARLY AT SHORT DISTANCE FROM PLACES IN WHICH EXPLOSIONS ARE LIKELY TO BE INITIATED

9.4.1. General information

Stone dust barriers, discussed in previous sections, found a very wide use in mines and had in many cases restricted the range of coal dust explosions preventing greater disasters. Therefore, they are used in accordance with the requirements of the pertinent strategy as discussed separately. The scope of the use of stone barriers is indicated, for example, by the number of such barriers erected in Polish bituminous coal mines amounting to approximately 3200. Unfortunately, stone dust barriers can stop explosions effectively only at the distance of about 60 m from the places where the explosions were initiated.

A coal dust explosion will cause the more serious consequences the longer is the way over which it develops. For this reason alone it is most advisable to restrict its range as much as possible. There are many cases in which the impossibility of locating a stone dust barrier at shorter distances than 60 m from the gallery's face creates a great hazard. To the

disadvantages of barriers the fact should be counted that they occupy relatively long sections of workings.

The length of the barrier depends upon the cross section of the gallery. For instance, in nonmethane fields in the narrowest galleries (2.5 m) with yieldable arch the length of the zone of the barrier, the shelves of which are 35 cm broad, amounts to about 50 m and to about 28 m if the shelves are 50 cm broad.

Analogously in the broadest galleries (5.7 m) with yieldable arch the length of the zone of the barrier, with shelves 35 cm broad, amounts to about 76 m and in the case of shelves 50 cm broad to about 42 m.

In methane fields the lengths of the barrier zones amount to twice as much as in nonmethane fields.

The progress in the science of electronics opened the possibilities of new solutions in the form of anti-explosion barriers automatically put into action based on principles entirely different from those applied in the case of the barriers used up to the present time.

First works in this field were carried out in Belgium [151], in Great Britain [95], in France [174], in the German Democratic Republic [94], in the Federal Republic of Germany [8], in USA [101], [125], in the Hungarian People's Republic [6], in USSR [130].

In the *EM Barbara* investigations on this problem were begun in 1970. According to their various uses triggered barriers may be classified as follows:

— barriers for stopping methane and coal dust explosions in the vicinity of the gallery's face,

— barriers for stopping local methane and coal dust explosions caused through the work of coal cutting machines,

— barriers for stopping coal dust explosions farther away from the gallery's face,

— barriers for stopping methane explosions in pipe conduits.

Up to date these works, though rather far advanced, had not achieved the success of having such barriers introduced for use in mines. However, they did succeed in working out a general scheme of the triggered barrier which consists of three basic elements:

— transducers or the element which reacts to the selected explosion parameter (pressure, temperature, radiation),

— the operational element which in response to the impulse received from the transducer puts the barrier proper into action and disperses the substance that serves to extinguish the flame,

— the extinguishing factor in the form of the limestone dust, water, sodium or potassium bicarbonate or a neutral gas such as nitrogen, carbon dioxide.

The essential purpose of a triggered barrier is that it should act in as close a neighborhood of the explosion initiator as possible, thereby preventing the development of the explosion. The moment of putting the barrier into action ought to be selected so as to assure the maximum effectiveness of the extinguishing substance with as small a quantity of it as possible.

The optimal moment for the dispersion of the extinguishing substance can be selected most easily for triggered barriers located at a very short distance from the place at which the explosion is likely to be initiated. A much more difficult problem is that of dispersing the extinguishing substance at a most opportune moment, in relation to the position of the front of the explosion flame, in cases when triggered barriers are located at longer distances from the place of the likely initiation of the explosion. This problem is very important, especially to the American *room and pillars* exploitation system. In such conditions rather complex arrangements will be required in order to achieve a high effectiveness of triggered barriers.

9.4.2. Transducers

The essential element of the triggered barrier, the element which makes this barrier actually "automatic," is the transducer or detector which reacts to the selected explosion parameter. As far as the choice of such parameters is concerned the following kinds of transducers may be mentioned as the most promising ones:

— the thermic detectors (thermocouples, thermistors, etc.) tested in Great Britain, France, the FRG and Belgium,

— the photoelectric detectors, sensitive to ultraviolet radiation, tested in the USA, Great Britain and France,

— the photoelectric detectors, sensitive to infrared radiation, tested in the USSR,

— the piezoelectric quartz or barium titanate detectors tested in Poland and in the GDR.

The greater hopes are now attached to optical detectors since there is no explosion without a flame. The selection of the radiation of the invisible rays of the spectrum is dictated by the necessity to prevent the putting of the barrier into action by extraneous radiation, for example, by the sources of light permitted in mines. As a rule the lighting in mines imitates a light of the wave length above 0.4 μm. The flame detector of a maximum sensitivity to infrared radiation must be equipped with suitable filters in order not to reach to the rays of the above indicated wave lengths. The curves of the radiation intensiveness of methane rays, ob-

tained by American investigators, show that below 0.4 μm the radiation of the flame is so weak that it does not permit the use as detectors of photocells, light dependent resistors or of photomultipliers with filters.

Possibly the Geiger-Müller counters could be used as detectors of ultraviolet radiation as they function quite well under conditions prevailing in mines. However, they are exposed to the danger of a fortuitous influence of the cosmic radiation which has to be taken into consideration in mines. But there is another factor that puts the detectors of ultraviolet rays above the detectors of infrared rays, namely, the high absorbing power of water droplets suspended in the mine atmosphere with regard to infrared rays. To ultraviolet rays these droplets are but a small obstacle. But coal dust is an impediment to these rays.

In a short recapitulation of what was stated above it ought to be pointed out that optical detectors should be insensitive to the following extraneous factors:

— the radiation of the sources of light in mines, electric and friction sparks,
— the cosmic radiation,
— the magnetic field of electrical appliances used in mines,
— vibrations,
— humidity,
— dust,
— the blast of the ordinary shotfiring operations.

Thus the demands toward the detectors are rather stiff.

9.4.3. Operational appliances

A triggered barrier may be put into action:
— by a mechanical device,
— by a detonating fuse ignited with a keen electric detonator,
— by a compressed neutral gas,
— by an explosive.

The neutral gas is most effective in dispersing the extinguishing material. The neutral gas itself as, for example, nitrogen let out from containers (introduced into the gallery) at a right moment and within a short space of time gives excellent effects as has been demonstrated by tests carried out at the experimental station in the Federal Republic of Germany [8]; in this way methane explosions have been extinguished. The tests in question, however, corresponded in their character to laboratory experiments because the containers with the neutral gas had been situated outside the surface experimental gallery. In such conditions the putting of the barrier into action requires the use of special valves that

can be opened quickly enough and are able to transmit a large quantity of gas within a very short time.

A much more simple way, easy to introduce and very effective at that, is the use of the detonating fuse for dispersing the extinguishing material.

The triggered barriers discussed here assume a particular importance in cases of the very rapid advance of the face when the coal is mined mechanically. In a methane seam the gas comes out from the comminuted coal at such a speed that at the very face of the gallery, where the coal is attacked by the cutting elements, it is impossible to avoid the formation of an explosive mixture of methane. This mixture becomes very easily and quite frequently ignited as a result of the friction or of the impact of the cutting elements against sandstone, or pyrite. Such conditions are very dangerous particularly because coal-cutting machines produce great quantities of very dangerous coal dust in the presence of which an explosion can be initiated very easily by the ignition of methane.

To combat this danger a barrier has been designed in the USA [101] to stop the development of a methane and coal dust explosion close by the very face of the gallery. In Fig. 9.62 a schematic view of this barrier is given.

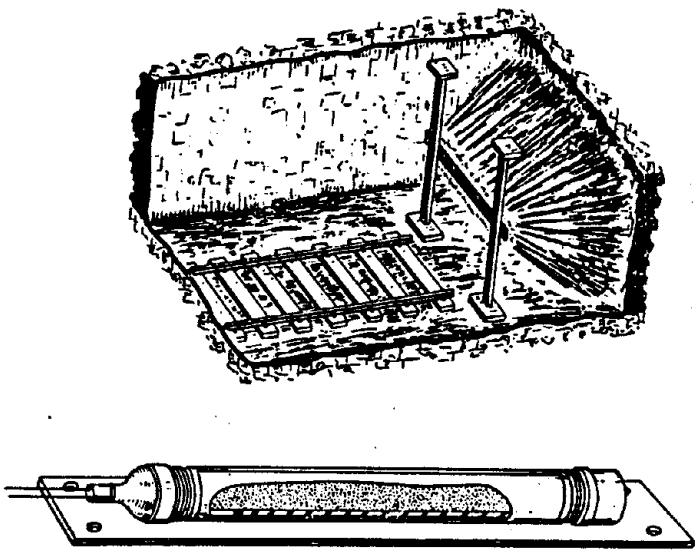


Fig. 9.62. A gallery face triggered barrier designed in the USA.

In Fig. 9.63 the extinguishing appliance is shown which is in use in the *EM Barbara* and gives satisfaction. It resembles in most details the appliance [95] previously in use in Great Britain.

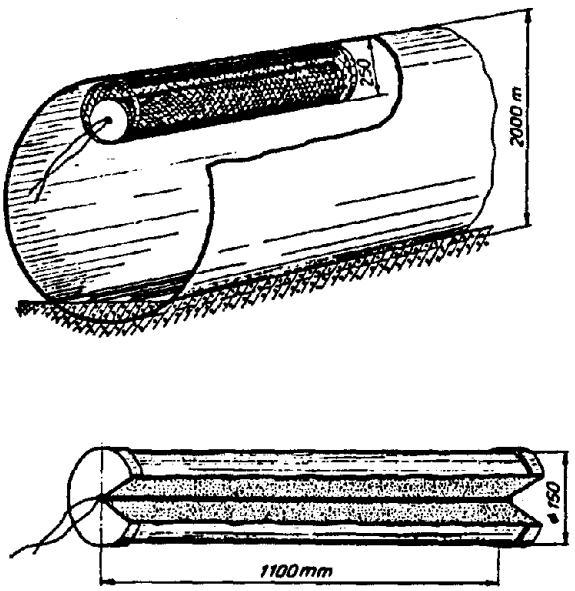


Fig. 9.63. A container for extinguishing coal dust and methane explosions used in the investigations carried out in the *EM Barbara* based on the *Buxton* model.

In the surface experimental gallery of the cross secttion measuring 3 sq m in the *EM Barbara* strong coal dust explosions have been stopped with the quantity of water $Q = 12.1$ kg/sq m at the distance of 20 m from this gallery's face. On this problem, however, many tests have yet to be made, especially in galleries of larger cross sections.

9.5. PROTECTING ZONES AGAINST THE PROPAGATION OF EXPLOSIONS

9.5.1. General information

It can happen that the erection of stone dust or water barriers in mines meets with insurmountable operational difficulties.

In such cases protecting zones are employed which serve instead of stone dust barriers. Such zones are sections of workings of a suitable length intensively dusted with stone dust. As a rule the mine dust in these zones ought to contain 80 percent of incombustible solid matter. Frequently, however, the lengths of such zones and the content in their dust of incombustible solid matter are questionable. The doubts of this kind certainly touch the essential points.

In no case the zones with mine dust containing 80 percent of incombustible solid matter should be treated as protecting zones which can be

used in the place of stone dust barriers. This has been confirmed by the results of investigations on the prevention of the propagation of coal dust explosion by dusting the workings with stone dust. The pertinent results are given in Section 6.5.

According to these results the contents of incombustible solid matter much above 80 percent are necessary in order to prevent the propagation of an explosion of the $d85$ coal dust over the distance of 200 m when a strong explosion initiator is used. Coal dust containing 80 percent of incombustible solid matter is still capable of propagating an explosion. If it were assumed that the protecting zone is 400 m long the necessary content of incombustible solid matter would have been 81.5 percent to give an adequate protection against the propagation of an explosion with the probability $P = 10^{-3}$. This applies to coal containing more than 25 percent of volatile matter — that it to say, to the majority of coals mined in Poland.

It should be remembered that if an explosion is to be stopped within a zone 400 m long the explosion in question would have covered already a very long distance with serious consequences to the crew. Such an issue cannot be regarded as equivalent to the action of a barrier which stops an explosion on the spot — that is, within the zone occupied by the barrier or at a short distance beyond that zone. A protecting zone should assure the stoppage of an explosion within a zone shorter than 200 m.

If coal dust is made safe by the dusting with stone dust in all workings of a mine in which it is present, with the exception of the coal mining workings, and if it is required that the content of incombustible solid matter in the dust of such workings be equal to at least 80 percent, then the protecting zones described above have no sense whatever. The view expressed now and again that protecting zones as described above can be used as substitutes for stone dust barriers is not only nonsensical, but actually harmful. The more so since the mines would have eagerly adopted the idea of employing the protecting zones instead of barriers in good many cases especially in such workings in which coal dust accumulates in small quantities only. Actually it would have been more proper to call the zones in question the zones intensively dusted with stone dust rather than calling them protecting zones.

Only such zones can well be regarded as protecting zones which contain pure stone dust or in which the stone dust does not contain more than 5 percent of coal dust. The zones of this kind are difficult to maintain except in the workings in which coal dust accumulates in quite insignificant quantities. Such zones cannot be regarded as equivalent to stone dust barriers: they serve rather as auxiliary zones which, nevertheless, in certain conditions can play a very important role.

Zones very strongly dusted with stone dust in which the mine dust contains more incombustible solid matter than is required by regulations are effective and recommendable beyond the bends of galleries, as has been demonstrated by investigations described in Section 9.1.11.

The same kind of zones play a very important part as auxiliary zones at the places at which stone dust barriers are located. More than once their great importance has been underlined when the effectiveness of stone dust barriers had been discussed.

In any case when making use of the zones intensively stone dusted waterproof stone dust ought to be used. The waterprof stone dust has to be regarded as more reliable than the ordinary stone dust because — in workings the air of which is highly humid — it retains its high degree of dispersibility during a long time.

Analogously to the zones strongly stone dusted, which (as has already been explained) are used of necessity but cannot be used instead of stone dust barriers, the zones may be used in which coal dust is very strongly humidified. In the last named zones coal dust should contain at least 50 percent of water.

The zones in which coal dust is strongly humidified may be used, naturally, only in such fields where the spraying of coal dust with water is the basic means of making this dust safe. In whatever place the employment of water barriers is found to be really impossible, owing to local difficulties, resort should be made to the zones of significant humidification of coal dust on sections not shorter than 200 m, unless the coal dust zones one deals with are altogether shorter.

9.5.2. Investigations concerning protecting zones of pure stone dust

Zones of pure stone dust create, naturally, ideal conditions. In practice even in coal workings where coal dust accumulations are very insignificant there is always a certain quantity of this dust present. However, if the relevant zone is freshly and very accurately dusted with stone dust so that only stone dust covers the external surface of the working, such conditions correspond to the presence of pure stone dust because, during the explosion, the blast raises the surface layer of the dust and in this case the layer in question consists of pure stone dust. Investigations of zones in which the dust contains up to 90 percent of incombustible solid matter were described in Section 6.5.

The numerous experiments carried out in connection with the problem of protecting zones of stone dust had never been published anywhere so far, and are described exclusively in the documentation of the *EM Bar-*

bara [49]. These experiments were performed with the use of various explosion initiators, in the 200 and 400 m experimental galleries, as well as initiating the explosions in the parallel gallery and in the connecting crosscut. In the present section the results of these experiments are being summarized.

The difficulty of stopping an explosion by a protecting zone grows with the distance between this zone and the place at which the explosion had been initiated. It grows also with the degree of the violence of the explosion; the possibility of very weak explosions passing through a protecting zone of stone dust will be discussed later on.

It may be generally stated that the most difficult explosions to be stopped by protecting zones are those that possess extreme characteristics — that is, very violent and very weak explosions alike. It is both interesting and reasonable that an analogous phenomenon is observed in the case of the stoppage of explosions with barriers. The investigations on the effectiveness of protecting zones were carried out mostly at distances of from 120 to 300 m from the gallery's face, and only infrequently at shorter distances. The length of the zone with pure stone dust was varied within the limits of 50 and 150 m. The whole cross section of the working had been dusted with stone dust. The quantity of stone dust oscillated between 140 and 420 kg/sq m. The indicated value refers to the entire stone-dusted zone — that is, it represents the total quantity of stone dust spread in the given zone. Flame velocities before the protecting zone ranged from about 300 to as much as 2000 m/sec. In most cases they amounted to about 800 m/sec.

The investigations discussed here were performed with the intention of using the protecting zone not only for stopping explosions but also for mitigating their consequences, for an explosion not restrained by a protecting zone is likely to cause far going damages on the surface. Therefore, the examination of protecting zones was carried out very frequently on the occasion of investigating the effectiveness of barriers. When one intends to determine the size of the barrier which would exactly suffice to prevent the propagation of an explosion, one has to take into account the possibility of the barrier failing to stop the explosion. Explosions of a medium and of a high degree of violence were as a rule stopped by the protecting zone of stone dust about 100 m long. Even with shorter zones, about 60 m long, the explosions were stopped in the majority of cases. On the whole it had been a rare occurrence that an explosion did pass the zone of pure stone dust.

As an illustration of the way in which a very violent explosion has been stopped by a zone of limestone dust 120 m long in Fig. 9.64 a diagram is given of explosion No. 482 initiated in the connecting crosscut

and developed further in the 400 m gallery. This explosion was not stopped by a barrier of limestone dust $Q = 200$ kg/sq m located at the distance from 200 to 270 m from the place where the explosion had been initiated, yet has been stopped by the protecting zone in spite of the fact that the explosion flame velocity before this zone amounted to about 1400 m/sec.

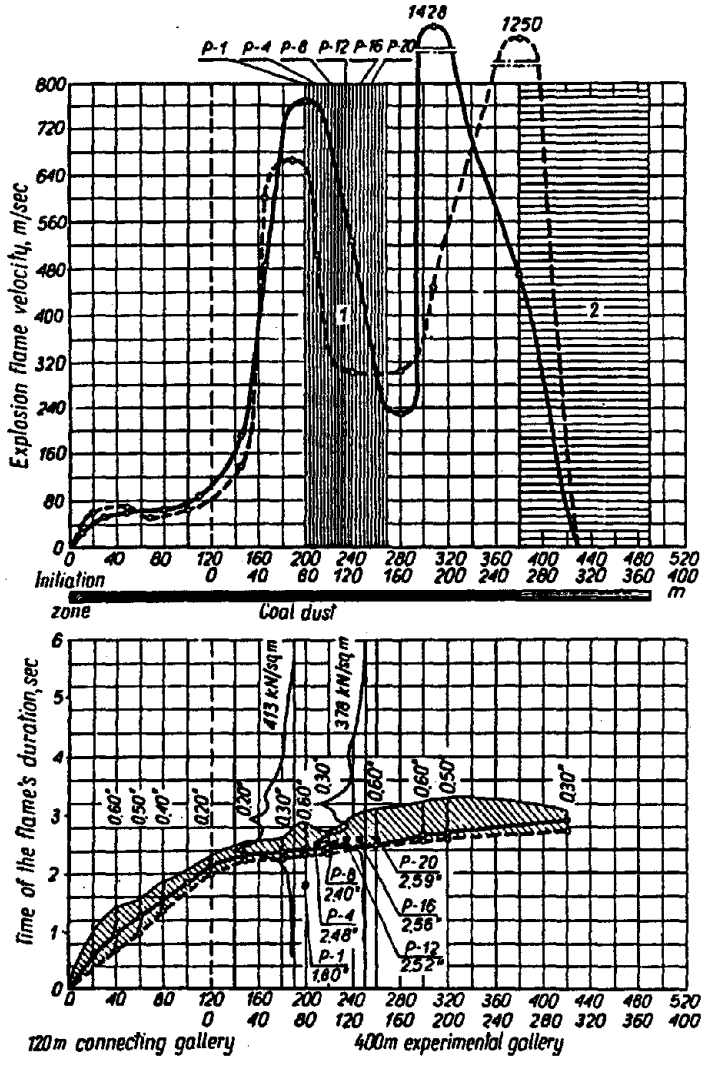


Fig. 9.64. A diagram of explosion No. 482 of the d25 natural coal dust, $n = 20\%$, initiator: 10mPII in the connecting gallery; *1* — stone dust barrier of 24 shelves, 1500 kg of stone dust, $Q = 200$ kg/sq m; *2* — protecting zone of stone dust, $Q = 330.5$ kg/sq m. Symbols as in Fig. 6.4.

In Fig. 9.65 a diagram is presented of explosion No. 945 not stopped by a stone dust barrier $Q = 67$ kg/sq m located at the distance of 40 m from the place of the initiation of the explosion close beyond a two-directional bend of the gallery. This explosion had likewise not been stopped by a protecting zone of limestone dust $Q = 220$ kg/sq m situated at the distance of from 180 to 260 m from the place of the initiation of the explosion — that is, by a zone 80 m long. The flame's velocity before the protecting zone amounted to about 300 m/sec.

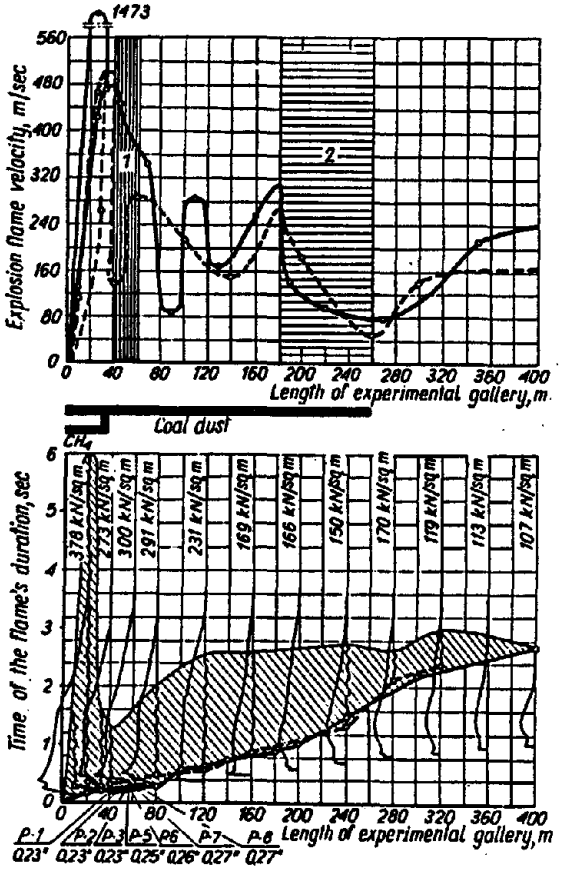


Fig. 9.65. A diagram of explosion No. 945 of the d25 natural coal dust, $n = 20\%$, initiator: 50 cu m CH_4 (9.5%); *1* — in the parallel gallery, close beyond the two-directional gallery bend, stone dust barrier of 8 shelves, 500 kg of stone dust, $Q = 66.7$ kg/sq m; *2* — protecting zone of stone dust, $Q = 220$ kg/sq m. Symbols as in Fig. 6.4.

Protecting zones of limestone dust can be very effective as demonstrated by numerous experiments, but it is absolutely essential to satisfy the condition requiring that the dusting with stone dust be supplemented

in such zones so often as to make certain that no pure coal dust will be found on the surface of the stone dust. For it ought to be stressed that the investigations described here were carried out under conditions of the perfectly fresh dusting of the examined zones with limestone dust.

The stone dusted zones, situated close beyond gallery bends, proved to be very effective. Even the zones 50 m long and, at that, with incombustible solid matter content in the dust of only 80 percent are effective provided that they begin close to the bend. Obviously zones of pure stone dust are even more effective.

When the zones are too short, for example, 30 m long and the content of incombustible solid matter in the dust amounts to 70 percent, as required in nonmethane seams, they are quite ineffective even if situated beyond gallery bends as shown in Fig. 9.66.

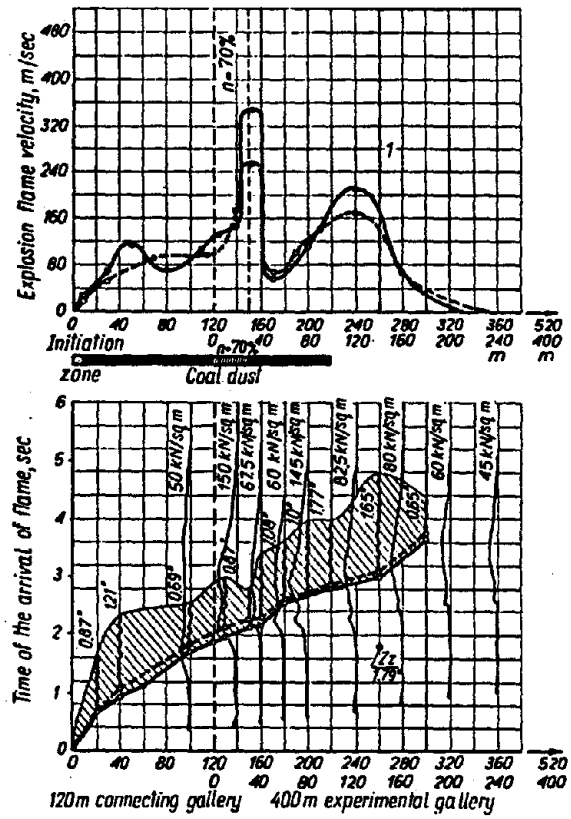


Fig. 9.66. A diagram of explosion No. 205 of the d25 natural coal dust, $n = 20\%$ initiator: 10mPII in the connecting gallery, protecting zone 30 m long ($n = 70\%$) close beyond the bend at the junction of the connecting gallery and the 400 m gallery; *1* — stone dust protecting barrier, 337 kg of dust, $Q = 45$ kg/sq m. *Zz* — means protecting barrier.

An unusual phenomenon had been observed in connection with very weak explosions initiated by the roof accumulations of methane. In a number of cases a very weak explosion did pass through a zone of pure stone dust. Though it is true that in the relevant experiments the protecting zones had been short — they were only 100 m long — yet the flame of the explosion passed through these zones as if they were not there at all; they did not cause any reduction of the velocity of the flame. This shows that the blast, being very weak, raised such an insignificant quantity of stone dust that it had no influence on the development of the explosion flame in the coal dust cloud which was passing through the protecting zone.

In the case of the presence beyond the protecting zone of a dangerous dry coal dust the explosion of this dust could have developed in a very violent way. This phenomenon is illustrated by the diagram of explosion No. 1240 in Fig. 9.55*a*, and by the diagram of explosion No. 1371 in Fig. 9.67.

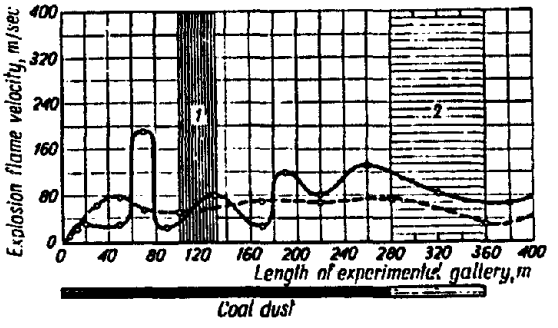


Fig. 9.67. A diagram of explosion No. 1371 of coal dust (up to the barrier — the *d*25, in the zone of the barrier and beyond this zone — the *d*85 coal dust); *1* — water barrier of 12 two-container sets, 900 kg of water, the polystyrene containers of Polish make placed loosely lengthwise along both sidewalls on frames, $Q = 120$ kg/sq m; the barrier did not stop the explosion; *2* — protecting zone of stone dust, $Q = 220$ kg/sq m.

The velocity of the flame before the protecting zone in explosion No. 1240 amounted to 60 m/sec, the length of the zone — to 100 m. The velocity of the flame before the protecting zone in explosion No. 1371 amounted to 80 m/sec and the length of the zone had been 80 m.

One may be justified in assuming that zones with pure stone dust, at least twice as long as the zones used in the experiments, would stop the development of a very weak coal dust explosion. But there is no experimental confirmation of this assertion. The size of the coal dust clouds preceding the flame is of very considerable importance here. This

size depends on the length of the way covered by the explosion flame before it reached the protecting zone.

Of great importance are the zones in which the dusting with stone dust is very intensive as well as the zones of a high degree of humidification of coal dust at the places in which stone dust or water barriers are located. All of the numerous experiments performed had confirmed the fact that such zones very distinctly heighten the effectiveness of barriers assuring for them a very high factor of security. This problem has been discussed in Sections 9.1 and 9.2.

10. THE EXPLOSIBILITY AND EXPLOSIONS OF LIGNITE DUST OF XYLITE STRUCTURE

10.1. GENERAL INFORMATION

All of the problems of coal dust explosions discussed so far referred to bituminous coals. For reasons of clarity the problem of the explosibility of lignite dusts is dealt with in a separate chapter, for brown coals differ essentially from bituminous coals in all their properties, brown coals being considerably younger. For the sake of simplicity, brown coals discussed here will be called "lignite." Lignite preserves its xylite structure and is to be found along the western frontiers of Poland in the voivodships of Wrocław and of Zielona Góra. In the region of Konin the brown coal found there retains partly the xylite structure, but partly it represents the so-called smudge coal variety.

In the period between the wars H. Hanel carried through certain investigations on the explosibility of brown-coal dusts in very short surface experimental gallery belonging to the experimental station at Freiberg. The author of the present book had no access to the publication of H. Hanel which appeared at that time. However, his investigations were performed on a very small scale because of the shortness of the surface gallery. The fundamental investigations on the explosibility of brown coals, on a large scale, were carried out first of all in the *EM Barbara* [39]. The coals used in these investigations came from the mines: *Sieniawa, Lubań, Przyjaźń Narodów, Kaławsk, Sieniawa-Smogóry, Sieniawa-Lubuska, Maria.*

The explosibility of lignite dust can play a role of real importance in deep mines. Actually deep working is done in the deep mines: *Kaławsk* at Kaławsk, *Przyjaźń Narodów* at Łuknica, and *Sieniawa* at Sieniawa. These mines have a much smaller output than the strip mines.

Strip mines have, unquestionably, the largest share in the output of lignite coals. Consequently the problem of the explosibility of lignite dust is of considerably smaller importance than that concerning the dust of bituminous coals.

The examined coals contained about 60 percent of volatile matter reduced to dry-ash-free carbon substance.

Lignite coals contain from 5.7 to 10.8 percent of hygroscopic water, but they are marked out by a very high content of free water. It is particularly characteristic of the lignite dust that it still retains its dispersibility with the content of the natural free water as high as 40 percent. This fact made it possible to examine the effectiveness of water in the task of impeding the explosion of the dispersible coal dust. It was found that natural free water is approximately 4.2 times more effective in action than the presence of incombustible solid matter when a weak explosion initiator is used. The effectiveness of free water diminishes with the growth of the strength of the initiator and becomes equal to the effectiveness of incombustible solid matter when the initiator is very strong.

Under conditions created by strong initiators water added to lignite dust through spraying has been found considerably less effective than water so added to bitiminous coal dust.

Lignite coals lose their content of free water very slowly; for instance, in order to reduce this content to about 10 percent, the lowest percentage obtained in the investigations discussed here, the coal had had to be dried during about two months.

10.2. CONDITIONS OF INVESTIGATIONS

Investigations were carried out in the 100 m surface experimental gallery and in the 200 m underground experimental gallery. The explosibility of lignite dusts was tested with the use of direct initiators (750 g of gunpowder), and of the 50 cu m CH_4 (9.5%) and 30 mPII initiators.

The most difficult and the easiest dispersion conditions were procured for different tests.

As in the case of the basic investigations on the explosibility of bituminous coal dust the so-called medium (d25) and fine (d85) lignite dust was used.

10.3. EXPLOSIVE LIMITS OF LIGNITE DUSTS

In the investigations on the explosive limits of lignite dust concentrations the same symbols were used as in the case of the bituminous coal dust:

q_0 — the lowest concentration of lignite dust at which not once the propagation of an explosion had occurred, g/cu m;

q_m — the lowest concentration of lignite dust at which sometimes the propagation of an explosion did occur; q_m is thus the lower limit of lignite dust explosibility, g/cu m;

q_p — the lowest concentration of lignite dust at which the propagation of an explosion occurred every time, g/cu m;

Q_m — the highest concentration of lignite dust at which sometimes the propagation of an explosion did occur; Q_m is thus the upper limit of lignite dust explosibility; above this concentration propagation of explosion did not occur, g/cu m;

Q_0 — the maximum concentration of lignite dust at which no propagation of an explosion had been recorded.

The concentrations of lignite dust given above were also computed in terms of pure carbon substance. In such cases the symbols used were: q_{0w}, q_{mw}, q_{pw}, Q_{mw}, Q_{0w}.

The essential difference between the investigations on bituminous coals and those which concerned lignite coals consisted in the fact that bituminous coals were marked out by the very low content of free water, about 1 percent, in comparison with the very high content of free water in lignite coals — from 9.5 to 39.3 percent.

The results of the tests through which the limit explosive concentrations of the *d*25 and *d*85 lignite dusts were determined are given in Table 10.1. The table shows the lowest values that were found.

For the *d*25 lignite dust only q_0 and q_m were found owing to the encountered experimental difficulties. For the *d*25 lignite dust does not propagate an explosion as easily as the *d*85 lignite dust.

The specific surface of the examined *d*85 dusts amounted to approximately 3800 sq cm/g.

As it can be seen in Table 10.1 the lowest limit explosive concentrations of lignite dusts, sufficient to cause the propagation of an explosion, computed in terms of pure carbon substance, do not show any essential differences in comparison with the relevant values found for the bitumi-

Table 10.1

A List of the Limit Explosive Concentration of Lignite Dust

The kind of the lignite dust	$\frac{q_0}{q_{0w}}$ g/cu m	$\frac{q_m}{q_{mw}}$ g/cu m	$\frac{q_p}{q_{pw}}$ g/cu m	$\frac{Q_m}{Q_{mw}}$ g/cu m	$\frac{Q_0}{Q_{0w}}$ g/cu m
*d*85	$\frac{90}{59}$	$\frac{100}{65}$	$\frac{120}{69}$	$\frac{\sim 325}{\sim 180}$	$\frac{\sim 400}{\sim 250}$
*d*25	$\frac{180}{104}$	$\frac{200}{116}$	—	—	—

nous coal dust; $q_{m\,w} = 65$ g/cu m; $Q_{0\,w} = 59$ g/cu m. The highest limit explosive concentrations of the d85 lignite dust, on the other hand, is considerably below that of the bituminous coal dust: $Q_{m\,w}$ = about 180 g/cu m, $Q_{0\,w}$ = about 250 g/cu m.

In the outcome the limits of the explosibility of lignite dusts are distinctly narrower than those of the bituminous coal dusts.

10.4. INVESTIGATIONS ON THE EXPLOSIBILITY OF LIGNITE DUSTS

10.4.1. The explosibility of lignite dusts when the initiator is weak

The d25 lignite dust with the natural content of free water only with a considerable difficulty can propagate an explosion when the initiator is weak. For instance, the d25 dust containing about 40 percent of water does not propagate an explosion when the direct initiator is used. The same d25 dust with the content of free water $W_k = 17.4$ percent requires not much above 40 percent of incombustible matter to be incapable of propagating an explosion. The influence of the initiator upon the explosibility of the d25 lignite dust is a marked one; with a strong initiator this dust easily propagates an explosion. The d85 lignite dust with the natural content of free water easily propagates an explosion even if a weak initiator is used.

10.4.2. The explosibility of lignite dusts when the initiator is strong

The explosibility of lignite dusts had been investigated in particular with the use of strong initiators: 30mPII and 50 cu m CH_4 (9.5%). The results of these investigations are scheduled in Tables 10.2 and 10.3. The tests of the explosibility were performed with the aim of determining the content of incombustible matter at which the lignite dust became incapable of propagating an explosion, similarly to the tests concerning bituminous coal dusts.

In these tables the so-called original lignite dust — that is, the lignite dust initially supplied for the experiments, is distinguished from its mixture with limestone dust for short referred to as "the mixture."

In the formulas included in this section expressing the conditions in which lignite dusts are made incapable of propagating explosions the following symbols are used:

f — the number of experiments performed with the limit content of incombustible matter,

— **for the natural lignite dust:**

V — the content of volatile matter computed in terms of d.a.f. carbon substance, %,

p' — the content of ash, %,

W'_h — the content of hygroscopic water, %,

W'_k — the content of free water, %,

$W'_z = W'_h + W'_k$, %,

c' — the content of the carbon substance, %,

d — the content of the fraction below 75 μm, %;

— **for the mixture of the natural lignite dust with limestone dust:**

W_z — the joint content of W_h and W_k, %,

p — the content of ash, %,

p_k — the conent of stone dust, %,

c — the content of the pure carbon substance, %,

n — the content of incombustible solid matter: $p+p_k$, %,

n_r — the joint content of incombustible matter: W_z+p+p_k sufficient to make lignite dust (containing water) unable to propagate an explosion determined experimentally, %,

n_0 — the content of incombustible solid matter: $p+p_k$ in the dry lignite dust sufficient to prevent the propagation of an explosion assumed in the reasoning, since it does not appear directly in the experiments, %,

n_{0p} — the content of incombustible solid matter: $p+p_k$ in the dry lignite dust sufficient to prevent the propagation of an explosion computed according to the regression equation, %,

n_p — the content of incombustible solid matter in lignite dust sufficient to prevent the propagation of an explosion computed according to equations (10.1) or (10.4), %,

n_{cp} — the joint content of incombustible solid matter and of water (computed with the application of the coefficients of effectiveness) sufficient to prevent the propagation of a lignite dust explosion deduced from regression equations,

d_m — the content of the fraction below 75 μm, %,

W_p — the total content of water — that is, W_h+W_k sufficient to prevent the propagation of an explosion computed according to the regression equation, %,

r — the conversion coefficient for converting the percentage of the incombustible solid matter into the percentage of the total content of water as regards its ability to prevent the propagation of lignite dust explosions,

q — the conversion coefficient for converting the percentage of the total content of water into the percentage of incombustible solid matter as regards its ability to prevent the propagation of lignite dust explosions,

$m(n)$ — the mean difference between the value of n and the value computed according to regression equations,

$S_{m(n)}$ — the mean error $m(n)$,

Table 10.2

The Results of Investigations on the Explosibility of Lignite Dust when the 30mPH Initiator Was Used

The original dust								The mixture		
V, %	d, %	f	W_h' %	W_k' %	W' %	p', %	c', %	W, %	n, %	n_c, %
57.4	25	5	6.0	39.3	45.3	7.6	47.1	21.6	55.9	77.5
60.0	25	3	8.4	17.4	25.8	13.6	60.6	8.5	71.5	80.0
60.8	25	4	10.5	21.7	32.2	10.6	57.2	14.1	60.9	75.0
63.8	25	3	6.8	25.2	32.0	19.0	49.0	11.4	71.1	82.5
56.1	85	3	6.0	9.5	15.5	8.4	76.1	3.1	81.9	85.0
57.8	85	4	6.0	36.3	42.3	6.5	51.2	12.4	72.6	85.0
59.0	85	5	7.4	25.1	32.5	13.2	54.3	9.0	76.0	85.0
59.8	85	3	6.4	25.3	31.7	12.9	55.8	7.2	80.3	87.5
59.7	85	5	6.9	20.4	27.3	16.0	56.7	8.4	74.1	82.5
58.9	85	3	8.4	15.4	23.8	13.2	63.0	5.7	79.3	85.0
61.6	85	3	10.5	13.5	24.0	11.1	64.9	4.6	82.9	87.5
60.2	85	3	7.1	23.8	30.9	16.0	53.1	8.7	76.3	85.0

Table 10.3

The Results of Investigations on the Explosibility of Lignite Dust when the 50 cu m CH_4 Initiator Was Used

The original dust								The mixture		
V, %	d, %	f	W_h', %	W_k', %	W, %	p', %	c', %	W, %	n, %	n_c, %
60.0	25	3	8.4	17.4	25.8	13.6	60.6	10.6	64.4	75.0
60.8	25	3	10.5	21.7	32.2	10.6	57.2	16.9	53.1	70.0
60.9	25	3	6.8	19.6	26.3	17.0	56.6	10.5	67.0	77.5
58.8	85	3	4.4	30.5	34.9	7.6	57.5	13.7	63.8	77.5
58.8	85	5	5.7	35.2	40.9	6.8	52.3	17.6	59.9	77.5
59.0	85	3	7.4	25.1	32.5	13.2	54.3	13.5	64.0	77.5
59.7	85	5	6.9	20.4	27.3	16.0	56.7	8.4	74.1	82.5
59.0	85	4	8.4	13.5	21.9	13.0	64.9	5.9	76.6	82.5
60.0	85	1	8.4	14.2	22.6	14.8	62.6	53.9	10.8	64.7
61.6	85	2	10.5	13.5	24.0	11.1	64.9	6.5	76.0	82.5
60.2	85	4	7.1	23.8	30.9	16.0	53.1	8.7	76.3	85.0
60.2	85	3	6.5	23.9	30.4	13.4	56.2	10.8	69.2	80.0

S_n — the standard deviation from the regression equation value of the variable n,

S_m — the standard deviation from the regression equation value of the variable W,

R — the manifold correlation coefficient.

In view of the fact that in the experiments performed the increase of the content of water W_k did not cause any material lowering of the degree

of dispersibility of lignite dust (in contrast to the bituminous coal dust), when the general formulas were being worked out, W_k has not been separated. The total content of hygroscopic water W_h and of free water W_k, denoted by the symbol W_z, was operated with.

The values of n_c given in Table 10.2 are very interesting when compared with analogous magnitudes found for bituminous coal dust with the use of the same 30mPII initiator. For the $d25$ dust of the bituminous coal ($V \geqslant 30\%$) with the probability $P = 10^{-2}$ the analogous value of $n_c = 77.5$ percent; thus, within the experimental error limits, it does not differ from the value of n_c for the lignite dust.

For the $d85$ dust of bituminous coal, with the probability $P = 10^{-2}$, the analogous value of $n_c = 88.7$ percent this being also very close to the value of n_c in the case of lignite dust.

Apparently, therefore, the explosibility of the dust of the bituminous coals does not differ in any material way from that of the lignite dust. Actually, however, the dust of lignite coals is explosive in a slightly higher degree since in the relevant experiments it contained larger quantities of water than the bituminous coal dust. When the relevant values of n_c are being compared one should not forget that in the case of the lignite dust the water had been actually more effective than the incombustible solid matter.

In any case the fact that the values of n_c are numerically in keeping with each other for both kinds of dusts, as indicated above, is rather unexpected considering the enormous differences between the petrographic composition of the bituminous coals and that of lignites. One should mention also that the comparisons made above are only tentative in their character since the values of n_c for lignite dust were not found with the probability $P = 10^{-2}$.

10.5. GENERAL FORMULAS EXPRESSING CONDITIONS WHICH WILL PREVENT LIGNITE DUST FROM PROPAGATING EXPLOSIONS INITIATED WITH THE 30mPII INITIATOR [66]

On the basis of data included in Table 10.2 regression equation has been formulated

$$n_p = 100\frac{d+102}{d+130} - 1.22W_z \tag{10.1}$$

representing interdependences between the variables, for example, d and W_z, and regression equation

$$W_p = 0.79(n_{0p} - n) \tag{10.2}$$

where

$$n_{0p} = 100\frac{d+102}{d+130} \tag{10.3}$$

representing interdependences between W_p, n_{0p} and n.

In the above equations the variable V does not appear since within the limits of its range no differences were ascertained in the explosibility of lignite dusts.

Using equations (10.1) to (10.3) for various given values of d and W the values of n_p can be computed sufficient for preventing the propagation of lignite dust explosions; or, on the basis of the given values of d and n, the values of W_p can be computed which can prevent the propagation of the explosions of lignite dust. In practice equation (10.1) is likely to prove more important.

The mean value of the systematic error for the variable n_p amounts to: $m(n) = -0.229$. The standard deviation for this error $S_{m(n)} = 0.557$. The mean error of deviations of the values of n from equation (10.1) $S_n = 1.86$.

The analogous computation of the deviations of the values of W_z from the solutions of the regression equation for W_p has given: $m(W_z) = 0.180$ and $S_{m(W_z)} = 0.445$, as well as the mean error of the regression $S_{W_z} = 1.49$.

The mean errors S_n and S_{W_z} are small in comparison with the results of measurements taken of the examined variables, and it can hardly be expected that more accurate experimental results could be obtained.

How strongly the values of the variable n are dependent upon the results obtained through solving regression equation (10.1), or the values of the variable W_z upon the results obtained with the use of regression euqation (10.2) is demonstrated by the fact that the values of the correlation coefficients in both cases are close to the unit: $R_n = 0.974$, and $R_{W_z} = 0.955$.

Very interesting is the comparison of the conversion coefficients appearing in regression equations: for converting water into incombustible solid matter $q = 1.22$, and for converting incombustible solid matter into water $r = 0.79$ for the lignite dust, with the analogous magnitudes $q = 1.71$ and $r = 0.58$ for the bituminous coal dust.

As can be seen it follows from the above comparison that water is more effective in the case of the bituminous coal dust than in the case of the brown coal dust.

This fact is due to the circumstance that the investigations, on which this elaboration is based in its entirety, were carried out with the use of the lignite dust that has been dispersible in spite of the considerable

content in it of free water. In the case of the bituminous coal dust an addition of free water invariably diminished the dispersibility of the dust.

10.6. GENERAL FORMULAS EXPRESSING CONDITIONS WHICH WILL PREVENT LIGNITE DUST FROM PROPAGATING EXPLOSIONS INITIATED WITH THE 50 cu m CH_4 (9.5%) INITIATOR [66]

On the basis of the data contained in Table 10.3 regression equation has been formulated

$$n_p = 100\frac{d+91}{d+120} - 1.44W_z \tag{10.4}$$

describing the dependences between the variables n_p, d, W_z, and regression equation

$$W_p = 0.68(n_{0p} - n) \tag{10.5}$$

where

$$n_{0p} = 100\frac{d+91}{d+120} \tag{10.6}$$

describing the dependences between the variables W_p, n_{0p} and n. The application of these equations is quite analogous to that of the equations formulated with reference to the 30mPII initiator.

The mean value of the systematic error for the variable n_p amounts to $m(n) = -0.32$, the standard deviation of this error: $S_{m(n)} = 0.496$, the mean error of the deviation of the value of n from the result of the solution of equation (10.4) $S_n = 1.75$. Analogously, on the basis of the deviations of the values of W_z from regresion equation (10.5) one finds $m(W_z) = 0.046$ and $S_{m(w_z)} = 0.632$ as well as the mean error of the regression $S_{W_z} = 1.2$.

The correlation coefficients of equations (10.4) and (10.5) are close to the unit and amount to: $R_n = 0.988$ and $R_{W_z} = 0.988$.

10.7. NOMOGRAMS FOR FINDING THE CONTENTS OF INCOMBUSTIBLE SOLID MATTER IN LIGNITE DUST AND OF FREE WATER IN THIS DUST SUFFICING TO MAKE THE GIVEN DUST INCAPABLE OF PROPAGATING AN EXPLOSION

Using the formulas (10.1) and (10.2) worked out with reference to the strongest initiator 30mPII, or the formulas (10.4) and (10.5) which refer to the 50 cu m CH_4 initiator it should be remembered that the fineness of the dust expressed by the content of the fraction which goes through the 75 μm sieve refers to the "pure" lignite dust made use of in the ex-

periments as the initial material. When one deals with the lignite dust to which limestone dust had been added then the value of d should be found on the basis of the directly specified value of d_m.

The value of d has to be computed by using the following formula

$$d = \frac{100(d_m - 0.6n_0)}{100 - n_0} \tag{10.7}$$

Obviously when one deals with the "pure" — that is, with the natural lignite dust there is no need of the above computation. It should be noted that the coefficient 0.6 in the formula (10.7) at the value of n_0 corresponds to the average fineness of limestone dust.

Consequently when we are dealing with lignite dust to which limestone dust has been added the formula (10.1) becomes changed into the formula

$$n_p = 100\,\frac{d_m - 1.62n_0 + 102}{d_m - 1.90n_0 + 130} - 1.22\,W_z \tag{10.8}$$

In order to determine whether for the purpose of making the given lignite dust unable to propagate an explosion it is necessary to increase the content in it either of water or of incombustible solid matter, then certainly the value of W_p or of n_p has to be computed.

From the analysis of the collected sample of the dust the values of d_m, n and W are obtained.

Note that in contrast to the case of the hard coal dust through the analysis of the lignite dust the direct value of n is found. The value of n_0, however, which is needed in the computations has to be found from the formula

$$n_0 = \frac{n}{1 - \frac{W_z}{100}} \tag{10.9}$$

In order to make it possible to dispense with the computation of the values sought for, nomograms had been worked out analogous to the nomograms for the bituminous coal dust presented in Section 8.11.

The nomogram for the strongest 30mPII initiator is given in Fig. 10.1, and the nomogram for the 50 cu m CH_4 (9.5%) initiator in Fig. 10.2.

The use of these nomograms, like the use of nomograms for the dust of the bituminous coal, is very easy; it needs only the application of a ruler.

There is no difference between the ways of using the nomograms for either of the two initiators. Therefore, the discussion below refers to the use of the nomograms given in Fig. 10.1 for the 30mPII initiator.

In order to find the values of n_p or of W_p the same data from the

analysis of the dust are necessary as the ones which served in the task of the formulation of equations (10.1) and (10.2). It is, therefore, always necessary to find the value of n_0 on the basis of the value of n established directly and to this end formula (10.9) has to be used.

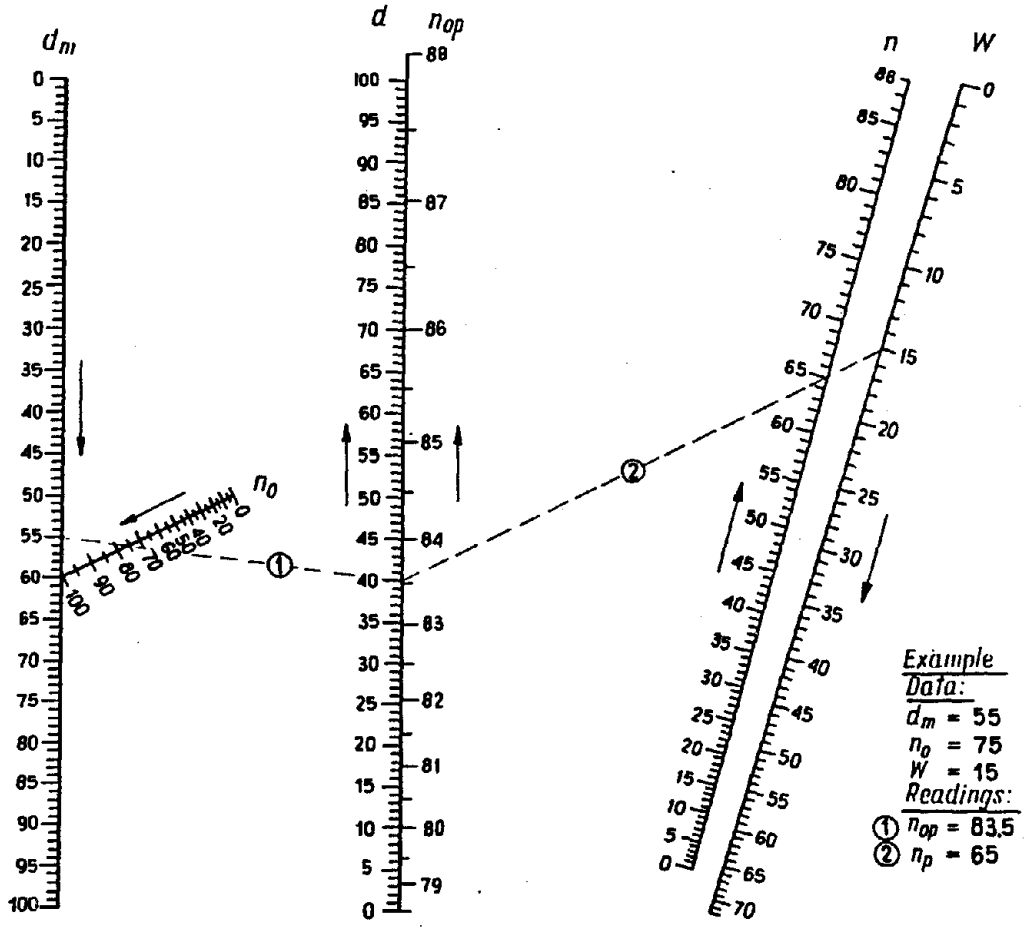


Fig. 10.1. A nomogram for finding the contents of incombustible solid matter and of water in lignite dust unable to propagate an explosion; the nomogram has been worked out on the basis of formulas (10.1) and (10.2); (the conditions assumed: the strongest 30mPII initiator and the easiest dispersion conditions).

It should be mentioned that the dust of lignites found in mines always contains water. Consequently the values of n_0 and n_{0p} which are found are of importance exclusively in connection with the fact that they are used in the nomograms or in the computations.

When the values of d_m, n_0 and W_r are known the following steps have to be taken in order to find the values of either n_p or W_p: on the scaled

line d_m one finds the point corresponding to the given value of d_m; on the scaled line n_0 the point corresponding to the given value of n_0 is found. Joining these two points with a straight line *1* and continuing this line until it crosses the scaled line d (n_{0p}), the value of d (which is not really of any direct interest) is found on the last named line. The point in question, however, determines at the same time the magnitude n_{0p}.

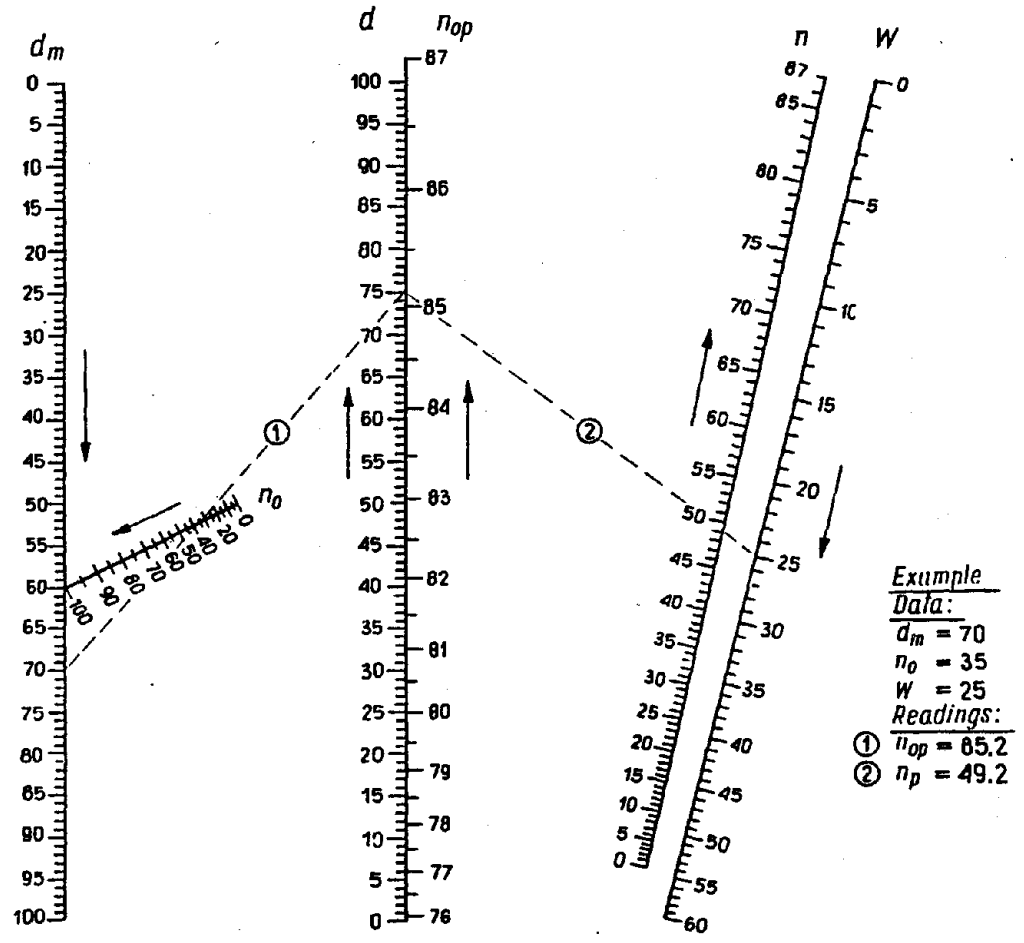


Fig. 10.2. A nomogram for finding the contents of incombustible solid matter and of water in lignite dust sufficient to make the given lignite dust unable to propagate an explosion; the nomogram has been worked out on the basis of formulas (10.4) and (10.5); (the conditions assumed: the 50 cu m CH_4 (9.5%) initiator, the easiest dispersion conditions).

If it is desired to seek the value of W_p then on the scaled line n the point corresponding to the value of n of the given dust has to be found. This point has to be connected by the straight line *2* with the point

previously found on the scaled line d (n_{0p}) and the line 2 should be continued until it crosses the scaled line W. The point at which the line crosses the scaled line W corresponds to the value of W_p which is read on the scaled line W_z. If the analytically established value of W of the given lignite dust is higher than that of W_p, the dust in question is unable to propagate an explosion. If the reverse is true then, in order to make the dust safe, it is necessary to increase its content of water or of limestone dust.

When looking for the value of n_p for the given value of W the point on the scaled line n_{0p}, corresponding to the found value of n_{0p}, has to be connected with the point determining the given value of W_z on the scaled line W. The point on the scaled line n, at which the connecting straight line 2 crosses this scaled line, determines the value of n_p.

If the analytically established value of n of the given lignite dust is higher than the value of n_p, the dust in question is not capable of propagating an explosion. If the reverse is true, then it is necessary to add limestone dust or water to the dust in question.

In such cases in which the lignite dust is to be made safe through the increase of its content of incombustible solid matter by means of dusting it with limestone dust, it is necessary to calculate the least quantity of the limestone dust which ought to be added to every weight unit of the lignite dust. Analogously to the method explained in Section 8.11 this weight unit coefficient, denoted by the symbol α can be determined by using the formula

$$\alpha = \frac{n_p - n}{100 - n_{0p}} \tag{10.10}$$

This coefficient remains the same for computations and for using the nomograms in reference to either of the two initiators: the 30mPII and the 50 cu m CH_4 (9.5%).

In order to make the lignite dust safe through the increase of its content of water by means of spraying it with water it is necessary to calculate the least quantity of water which ought to be added to every weight unit of the given lignite dust. This weight unit coefficient denoted by the symbol β can be determined by using the formula

$$\beta = \frac{n_p - n}{122 - n_p} \tag{10.11}$$

The above coefficient refers to computations pertaining to the 30mPII initiator. In the case of the 50 cu m CH_4 (9.5%) initiator this coefficient is expressed by the formula

$$\beta = \frac{n_p - n}{144 - n_{0p}} \tag{10.12}$$

The way of using the nomogram is best illustrated by the following example:

Data obtained as the result of the analysis of the lignite dust: $d_m = 55\%$, $n = 63.8\%$, $W_z = 15\%$. From formula (10.9) $n_0 = 75\%$ is obtained.

Assuming that the dusting with limestone dust is employed to make the lignite dust safe one finds from the nomogram shown in Fig. 10.1 the value of $n_{0p} = 83.5\%$ and the value of $n_p = 65\%$.

This is exactly the example given in Fig. 10.1.

Since $n = 63.8 < n_p = 65$ the lignite dust in question is not sufficiently safe as regards the propagation of an explosion.

The weight unit coefficient necessary for determining the quantity of stone dust to be added to the lignite dust computed according to the formula (10.10) amounts to: $\alpha = 0.073$.

The remarks concerning the use of the nomograms for the dust of bituminous coals, contained in Section 8.11.6, apply equally to the nomograms for the dust of lignites.

11. WHY DID THEY PERISH?

The remarks presented in this chapter are general in their character and do not refer to any particular country except when concrete examples are cited.

In the first chapter of this book a list was given of coal dust and methane explosion disasters which had occurred in the coal mines of the various coal districts of the world. Such list, though incomplete (apart from the accurate British statistics) create a strong feeling of despondency.

The total number of casualties in the explosion disasters in mines had actually been much greater than that given in the list. In many countries the relevant statistics were not accurate or were not published; this applies especially to explosions in which the death roll was not very long. Of course the total number of casualties is the sum of the numbers of victims of all mine accidents. The data to which the author of this book had the access referred in the main to the more serious disasters; yet the number of explosions with small numbers of casualties was much greater.

When reviewing the statistical data of explosion disasters since the time when the keeping of the relevant records began the most striking observation that can be made is that such disasters still continue to happen. Although the number of victims and the frequency with which the disasters of this type occur are diminishing, yet the fact of their occurrence up to this day, in their present dimensions and so frequently as they actually happen, cannot be justified.

In the attempt to answer the question contained in the title of this chapter three periods in the history of coal dust explosions can be distinguished.

The first period extends over long years during which the real causes of methane and coal dust explosions were not scientifically explored. It is true that the hazard of methane explosions had been recognized and the removal of methane by airing the workings introduced at an early stage; yet the means at the disposal of the coal industry at the time were primitive for both discovering the presence of methane and combating it. The hazard of coal dust explosions has been recognized much later at the end of the last century. During this first period the occurrence

of explosions can still be justified though a good will on the part of the colliery owners and state authorities could have restricted, at least at the close of the last century, the frequency and the range of explosions.

In the second period from the beginning of the present century until the World War II the coal industry, under the pressure of trade unions and of the public opinion, organized scientific research establishments, commonly called experimental stations, to investigate the problem of explosions in mines. These establishments were at first equipped extremely modestly in relation to their actual requirements, as well as in relation to the possibilities of the industry in this respect. Nevertheless, they produced very serious works.

During this period the level of the basic scientific disciplines had already been so high that a considerably more rapid progress of investigations on the methods of suppressing the hazard of coal dust explosions depended only on the funds alloted to the experimental stations. But the industry was interested neither in the acceleration of the progress of these works, nor in the achievement of concrete results which could be introduced to the mining practice because, of necessity, it would have caused an increase of the operational costs.

Actually there was an evident necessity of carrying out very extensive fundamental research works on the problem of explosions. But in the conditions then existing, the scientific research establishments were compelled to restrict to the minimum their basic researches and to concentrate their effort on the search for the prophylactic measures. Naturally such measures, not being founded on the adequately broad basic researches, could not represent a proper level. The problem of the stone dust and water barriers can be cited here as a classical example. Although Taffanel had been their inventor he failed to supply the conclusive evidence for the necessity of introducing the use of these barriers in mines, and his failure was due to the absence of the basic research works. The barriers of Taffanel had fallen short of expectations in the *Clarence* mine. Only the tests carried out later in Poland, in the USA and in Germany have led to the introduction of barriers as a very valuable means of stopping explosions.

As another example of the inadequate elaboration of the prophylactic measures may be cited the spraying with water of coal dust, a practice continued over a long time. This method had not been based on extensive research works conducted on a sufficiently large scale, endeavoring to explore the conditions of its effectivenes. It is an astonishing fact that the really thorough investigations on the influence of water upon the explosibility of coal dust were carried through only after the World War II. In mines the spraying with water was performed more often than not in

a rather formal manner. The complete saturation of coal dust with water was not achieved and the method of spraying with water was applied also to dry coal dust which, obviously, could not bring the desired effect. A lot of casualties in great mine disasters had had to occur before the defectiveness of such spraying of water, and the general limitations of the effectiveness of the method itself have been recognized.

In the end the spraying with water was replaced by the dusting with stone dust. But this method had not been thoroughly enough examined either. The conclusions were not always correctly drawn from the relevant tests. This is a further example of the inadequacy of basic investigations.

Since long ago it has been known that the range of the possible initiators of coal dust explosions, as it concerns their ability of initiating an explosion, is very wide in the conditions existing in mines.

Conclusions concerning the requisite content in the dust of incombustible solid matter were drawn from the results of experiments performed under conditions which did not correspond in the least to the most dangerous conditions occurring in mines; quite frequently the conditions of experiments were even less dangerous than the average conditions met with in mines. In consequence, in many countries, during a long time the dusting of workings with stone dust had been obligatory only to the extent which would suffice to bring the content of incombustible solid matter in the mine dust to the minimum level of 50 percent. This requirement is absolutely inadequate and the coal dust made "safe" in the way described above can explode with a great violence.

The occurrence of great disasters was required to cause the change of the relevant regulations in some countries. For instance, after the explosion in 1962 at the *Luisenthal* mine in which 299 miners have lost their lives the requirements concerning the content of incombustible solid matter in coal dust were raised immediately to 80 percent.

In some cases not even great disasters were taken as an inducement for drawing the necessary conclusions. In spite of fatal experiences (e.g., in the *Mikawa* mine disaster — 458 victims) it is not everywhere that the necessity is recognized of making the dangerous coal dust safe in all workings and not exclusively in the workings actually exploited.

The necessity of combating everywhere in mines the danger connected with the presence of methane is recognized generally as something more directly understandable. Consequently the regulations concerning the suppression of the methane hazard represent in the world coal industry in general a much higher scientific and technical level than the analogous regulations with regard to coal dust. On account of the tremendous role played by methane as the possible initiator of coal dust explosion, the fact

referred to above is a great step forward also in the fight against the explosions of coal dust.

Apart from assigning only inadequate funds to the research work on the problems of coal dust and methane explosions the industry tried to make the managers of the scientific research establishments entirely dependent on the industrial leadership. Actually the industry did more than just try: it exerted an undue influence on the establishments in question, particularly with reference to the prophylactic measures suggested by them.

As a very favorable development may be regarded the fact that in some countries the miners' trade unions undertook the partial financing of the work of the scientific research establishments. However, this was not carried into effect on a sufficiently large scale.

The following general observation is worthy of being made. The ascertainment of the hazard — the most thorough ascertainment of it in all of its aspects that can be met with in practice — supplies the premises for making a decision. The scientific research establishments, possessing naturally no executive authority, have to submit their entirely impartial opinions in these matters. If at the very foundation of the work of ascertaining the nature and magnitude of the hazard the freedom of expressing the opinions had been restricted, or the character of the opinions were to be interfered with — the consequences would have been undoubtedly disastrous.

The progress of the research work, however, continued to be relatively slow. Moreover the results of the investigations have not been taken full advantage of for the improvement of the mining regulations and, therefore, the hazard of the possible explosions in mines remained to be quite serious. The tremendously slow pace at which regulations are being altered is one of the factors contributing to this state of things to the satisfaction of the industry and even with its support.

Explosions, which continued to occur in consequence of the inadequate introduction of the measures developed by the progress of science, had become more and more inexcusable. Of course disasters did occur also as the result of the negligence in the fulfilment of the binding regulations. This negligence was and is caused in a great measure by the absence of a satisfactory supervision, and the lack of the sufficient knowledge, among the supervisors, of the problems connected with explosions.

In the third period, after the World War II, the scientific research establishments have been, generally speaking, equipped much better and the progress of the investigations on the problem of explosions became considerably quicker than before.

At the present time our knowledge in the domain of explosions in

mines and the prevention of accidents has moved considerably forward and achieved a level which, undoubtedly, allows to combat effectively the hazard discussed here. Unfortunately coal dust explosions happen to this day. The introduction of scientific achievements into the mining practice has become admittedly quicker now than it had been in the prewar period; yet the progress is still too slow.

During the postwar period the number of fundamental research works increased considerably. This makes possible a speedier formulation of practical proposals based on the results obtained at different stages of the investigations which are being carried out. Every scientific worker knows that in the course of a research work separate stages can be distinguished the results of which can be utilized gradually, while the research is continued. Unfortunately the opportunities of this kind are often defeated by the slow procedure of altering the existing regulations, an impediment already mentioned here.

It is absolutely necessary to ensure the possibility of altering any particular provision in the existing regulations as often as the progress of science will justify the alteration. Unfortunately this principle is not followed. To persist in maintaining obsolescent regulations in force is a practice very detrimental to the safety in mines and to the technical progress.

In the meantime the potential explosion hazard grows because, as the winning of coal descends to lower levels, the content of methane in the seams increases; the absolute methane evolution — that is, the quantity of methane evolved within a unit of time grows also with the speed of the advance of the working faces.

The mechanization of coal winning causes the growth of the methane and dust hazards. For instance, the combined cutter loaders in mine workings create a particularly great danger of methane and coal dust explosions since, with the very quick advance of the face and the large quantities of the evolved methane and the produced coal dust, respectively, per unit of time, the auxiliary ventilation may not always work effectively enough to reduce the concentration of methane below the limit of explosibility. The sparks, produced through the friction of the cutting elements against the sandstone, spherosiderite or pyrite very easily ignite methane. In such conditions the initiation of a coal dust explosion becomes very easy.

The conditions being such as above described the improvement of the prophylactic methods becomes a matter of great importance.

When necessary the competent authorities issue emergency decrees. The large number of such decrees makes the management of mines a very difficult task.

The highest legislative bodies usually have the best wish to assure through statutory regulations the greatest possible safety to miners and to base such regulations on the actually progressive knowledge. In Poland, for example, even in the most difficult postwar economic situation of the country in spite of the tremendous need of a rapid growth of the coal output, the authorities decidedly refused to increase the winning at the cost of exposing to danger the crews of mines.

It is necessary, however, that this attitude of the powers be realized at all levels of the mining hierarchy. New safety regulations (or the modernization of the old ones) are prepared as a rule by representatives of government departments, mining authorities, of the industry and the scientific research institutes. The Miners' Trade Union ought not to be left out from this work.

All the above mentioned institutions should unite their efforts for the common aim which must be the most effective suppression of the danger of explosions. Obviously the wholly objective findings of scientific investigations ought to be taken into accout as the foundation on which the regulation proposals must be based.

Naturally the conditions existing in mines have to be considered with the greatest accuracy because the regulations must be realizable and ought to show the way in which mines can be protected against explosions in all of the manifold conditions created by the mining operations.

In the discussions concerning new regulations there should be no "haggling," no bargaining over the "interests" of mines in the sense in which such interests were presented in the past when great disasters did take place even in conditions fully conforming to the regulations in force at the time.

Although the observations comprised in this chapter may seem to be imbued with pathos they are, nevertheless, necessary as the logical statement of the truth.

When new regulations are worked out the participants should be dominated by the spirit of the mutual understanding and the mutual desire of formulating requirements based on the latest achievements of knowledge and of technology being fully aware of the very dramatic experiences of many years in the past.

Those who prepare the projects of new regulations should be aware of their great responsibility.

In the process of mining we are confronted daily with operational difficulties and we are used to overcoming them. Accordingly deeper, therefore, should be our understanding of the necessity to overcome the difficulties met with in matters concerning the safety of work.

The history of mining knows many tragic examples of the allegedly

insurmountable operational difficulties und unrealizable requirements which, after a great disaster, proved to be easy both to overcome and to realize.

If the regulations were not prepared according to the above obvious precepts the question heading this chapter *Why did they perish?* would have to be supplemented by the guestion: *Why they can perish?*

Progress cannot be permanently stopped but it can be retarded. Such retardations caused many a disaster in the past. The advance of knowledge and technology makes it possible to realize the protection of mines against explosions with full consideration of the production economics.

By themselves, obviously, even the most perfect regulations cannot eliminate the hazard of explosions. Regulations must be complied with not only formally in order to avoid any unpleasantness from the mining authority, but with the awareness of their real purpose and with the proper technical understanding. Conditions in mines vary so much that it is impossible to formulate the detailed provisions in the regulations so as to meet absolutely all conditions.

Moreover it would have been very burdensome for mine supervisors if regulations were to resemble encyclopedias of mining. Regulations ought to be as concise as possible and include the most essential requirements. Their wording must assume that members of the supervising personnel possess an adequate knowledge for practising the mining profession, acquired in a university or in a technical school. The state of this knowledge ought to be controlled from time to time and the persons wanting in professional knowledge should not be confirmed as supervisors. The explanations advanced now and again that regulations did not formulate the reguirements in a concrete case with an adequate precision of detail are not always advanced in good faith. Seeking the prevention, as it were, of improper interpretation of the regulations by mine supervisors the authors make the regulations excessively voluminous and, at that, these regulations are supplemented by detailed instructions. A reasonable moderation is to be recommended in this matter as otherwise instructions can become, in actual use, a burden to mines.

On the other hand the mining authority when visiting a mine should not insist on the slavish fulfilment of requirements contained in regulations and instructions without considering the particularities of local conditions which may have created real difficulties not taken into account in the requirements. When mines are controlled the greatest attention should be paid to the essential problem: that of preventing explosions.

Of course such an understanding of regulations by the supervising personnel in mines, as well as by the mining authority, calls for a good knowledge on their part of the problem of explosions in mines. The more

thorough is their knowledge in this field the more effective and economical is the use of the prophylactic measures. This simple and understandable precept plays, and will continue to play, the fundamental role in the problem discussed here.

For obvious reasons the know-how and knowledge must be supplemented. The supplementary schooling of miners and mine supervisors is, therefore, a necessary postulate. Explosions in mines do not occur often. Hence the tendency to forget the hazard amid the rush of the daily work. At times one observes the inclination to accept a certain risk in matters of the explosion hazard. The supplementary schooling of miners aims, among other things, at reminding them about this particular aspect of the hazard.

Many observations included in this chapter are so obvious that they may seem to be superfluous. Yet the experience of many years, various accidents in the past as well as events of everyday life prove that it is proper to put the emphasis on these principles exactly in the last chapter of this book.

There are still two problems requiring accentuation.

It would have been disingenuous and unworthy of this book, based on scientific researches continuing many years and on data concerning explosions in mines, to leave out critical comments on the past and omit certain warnings concerning the future. It is self-evident that criticism is an indisputable necessity. The absence of criticism, or a certain timidity in expressing critical observations, is one of the answers to the question which makes the title of the present chapter.

There is also the humanitarian aspect.

Against the background of the hazard of explosion disasters discussed in this book there appears in a sharp outline the responsibility for the prevention of explosions. The entire history of the problem of explosions shows that if, in the treatment of this hazard, persons on executive positions in mining establishments were guided by humanitarian principles and by the sense of duty many a disaster could have been avoided. One could cite a number of facts irrefutably demonstrating the truth of the above statement. By way of an example reference can be made to Faraday's opinion of 1844 on the participation of coal dust in explosions. There was no response to this opinion. It is worth reminding ourselves also of the fact that the British Commission's report of 1894, declaring coal dust to be capable in itself of exploding, did not become current enough to sink into people's minds.

The above examples are taken from the fairly distant past. But the absence of humanitarian feelings and the lack of the sense of duty manifested themselves equally in the periods of time in which the problem of

the danger of explosions and of their consequences has already been well explored through scientific research work; they were quite obvious, particularly in connection with great disasters.

The last two concluding accents of this book, very mildly expressed, refer not only to the past but, naturally, are equally important as regards the future.

The author wishes to express his deepest gratitude to all workers of the Experimental Mine Barbara who participated in the research works continued through many years, and greatly assisted the author in the writing of this book.

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