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THE EXPLOSIBILITY OF COAL DUST

BY

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WITH CHAPTERS BY

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THE EXPLOSIBILITY OF COAL DUST.

By George S. Rice.

INTRODUCTORY STATEMENT.

THE COAL-DUST PROBLEM.

This bulletin traces the growth in the belief in the explosibility of coal dust, summarizes the experiments and mine investigations that have established this belief, and gives the present status of preventive measures. It has been prepared in accordance with the provisions of the acts of Congress authorizing investigations relating to the causes of mine explosions, and contains references to and descriptions of experiments made at the testing station of the United States Geological Survey at Pittsburg, Pa. This station was established and equipped for the purpose of carrying on investigations relating to mine explosions, fuels, and structural materials.

Only within comparatively few years has the dry dust of bituminous and lignitic coals been generally recognized as an explosive agent more insidious, threatening, and deadly to the miner than fire damp. Fire damp carries its own flag of warning—the "cap" in the safety lamp—but coal dust, though visible, does not attract attention until present in large quantities. Fire damp is of local occurrence, and except in notable and very exceptional cases is controllable by careful manipulation of ventilating currents. If by mischance a body of fire damp is ignited in a mine, the force of the explosion is terrific, but the effect is localized unless dry coal dust is present, or unless (as it very rarely happens) an explosible mixture of methane gas and air extends through large areas of the mine. In a dry mine dust accumulates everywhere, and the blast from the ignition and combustion of bituminous dust may traverse miles of rooms and entries and wreck structures at the entrance to the mine. The comparative potential destructiveness of gas and of bituminous dust is strikingly shown by the history of the Pennsylvania anthracite mines. These mines not infrequently have large inflows of gas, and the resulting mixtures of gas and air have sometimes been ignited, yet no such wide-sweeping explosions have taken place, despite the presence of dry anthracite dust, as have happened in excellently ventilated bituminous mines.

This bulletin, as is emphasized in the body of it, should be regarded as a preliminary study of the coal-dust problem. The pressure of other work and the almost continuous use of the explosives-testing apparatus at the Pittsburg station for the important work of investigating the relative safety of explosives for use in coal mines have limited the experiments that could be made dealing with methods of lessening the danger from coal dust. However, it is expected that opportunity will be afforded in the future to take up systematic experimenting both at the Pittsburg station and in the field along lines suggested by the results presented in this report.

ACKNOWLEDGMENTS.

The writer desires to express his thanks to Dr. J. A. Holmes, expert in charge of the technologic branch of the United States Geological Survey, for the inspiration of the studies undertaken, and to Mr. H. M. Wilson, chief engineer, for advice in the preparation and editing of the paper.

He also desires to acknowledge the great assistance given by his associates in the mine-accidents division, Messrs. Clarence Hall and J. W. Paul, Dr. J. C. Clement, Dr. J. C. W. Frazer, and the writer's assistants, Messrs. A. C. Ramsay and L. M. Jones.

The account of the investigations under way at experiment stations in Europe is by Mr. Axel Larsen, explosives expert, who, in connection with his work for the survey, visited these stations and examined their equipment.

The chapter on the use of steam as a preventive of dust explosions was prepared by Mr. Frank Haas, consulting engineer for the Consolidation Coal Company, and that on experiments with sprays in Oklahoma coal mines by Mr. Carl Scholz, vice-president of the Rock Island Coal Mining Company. Cordial acknowledgment is made of the interest shown by both these gentlemen in the study of the practical aspects of preventive measures, and of their kindness in preparing for presentation in this bulletin the results of their observations.

The chapter on laboratory investigations of the ignition of coal dust, by Dr. J. C. W. Frazer, a chemist of the Pittsburg station, gives a review of the laboratory and other small-scale experiments that have been made in the past and an account of the laboratory experiments undertaken by him and to be continued, on the relative explosibility of different coal dusts collected by mining engineers in different parts of the country.

The author's indebtedness to various foreign investigators is shown by the numerous quotations from their published works.

HISTORICAL REVIEW OF THE COAL-DUST QUESTION IN EUROPE.

OBSERVATIONS IN ENGLAND PRIOR TO 1850.

In the published account of an explosion in an English colliery, Wallsend, on September 3, 1803, J. Buddle, chief of the Newcastle coal miners, says: "The workings were very dry and dusty, and the survivors who were most distant from the points of explosion were burnt by the shower of red-hot sparks of ignited dust which were driven along by the force of the explosion."[a]

Robert Bald, in Jameson's Journal for 1828,[a] mentions the possibility of the flame from a fire-damp explosion igniting the coal dust strewn more or less thickly about the working places of a colliery.

In a book by W. N. and J. B. Atkinson, English inspectors of mines, entitled "Explosions in coal mines" (1886), page 132, there is a list of mine explosions in England prior to 1870, made from contemporaneous newspaper reports and inquest records. In certain explosions it was mentioned that coked dust was observed. Besides the explosion above noted, it was reported to have been found at the Jarrow explosion of August 3, 1830, at the Wallsend explosion of June 18, 1835, at the Springwell explosion, December 6, 1837, and at the Thornley explosion, August 5, 1843.

Professor Faraday, the famous chemist and physicist, remarked in his report on the Haswell colliery explosion, September, 1844:[a]

> In considering the extent of the fire from the moment of explosion it is not to be supposed that fire damp was its only fuel; the coal dust swept by the rush of wind and flame from the floor, roof, and walls of the works would instantly take fire and burn if there were oxygen enough present in the air to support its combustion; and we found the dust adhering to the faces of the pillars, props, and walls in the direction of and on the side toward the explosion, increasing gradually to a certain distance as we neared the place of ignition. The deposit was in some parts half an inch, in others almost an inch thick; it adhered together in a friable coked state. When examined with a glass, it presented the fused round form of burnt coal dust, and when examined chemically and compared with the coal itself, reduced to powder, was found deprived of the greater portion of the bitumen, and in some instances entirely destitute of it. There is every reason to believe that much coal gas was made from this dust in the very air itself in the mine by the flame of the fire damp which raised and swept it along, and much of the carbon of this dust remained unburnt only from want of air.

It may be remarked that many investigations of explosions since have established that coked and caked coal dust is more generally, though not invariably, deposited on the side of timbers and projections opposite to the direction from which the explosive wave approached. This is commented on by W. N. and J. B. Atkinson.[b]

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[a] Final Rept. Accidents in Mines Comm., 1886, p. 30.
[b] Explosions in coal mines, p. 25.

The remarkable evidence given by Faraday on the importance of coal dust as an explosive agent was overlooked for many years.

OBSERVATIONS BY FRENCH ENGINEERS PRIOR TO 1890.

The final report of the accidents in mines commission (1886) gives the following account (p. 31) of the first French publication on this subject:

> Although the reports of Faraday and Lyell were published in 1845, these publications appear to have remained long unknown in France, for in 1855 M. du Souich, chief government engineer of the Sainte Etienne Arrondissement, when referring to an explosion which had occurred at Firmininy, advanced as new the view that the deposition of crusts of light coke on the props was due to dust which had been swept up and transported to a distance by the violent current produced by the explosion and which, becoming in part inflamed, had extended and prolonged the destructive effects originated by the fire damp. On the occasion of two explosions in 1861 M. du Souich again dwelt upon his views regarding the part played by coal dust in increasing the disastrous effects of fire-damp explosions.

In 1867 M. Verpilleaux made some experiments with coal dust and concluded that it is an important factor in mine explosions. M. Vital, in 1875, while studying the effect of an explosion in a part of the Campagne colliery, France, where fire damp had never been found, made experiments and from the results decided that "very fine coal dust, rich in inflammable constituents, would increase the intensity of an explosion of fire damp and prolong its extent."

In 1882 M. Mallard and M. Le Chatelier, members of the French fire-damp commission, reported, as the result of their inquiries, that "they rejected the theory that coal dust was any serious danger, and maintained that no colliery explosion of any importance could be attributed with any probability to the action of coal dust."[a]

This unfortunate conclusion delayed recognition of the danger of coal dust in France for many years, and apparently the explosibility of coal dust did not receive general acceptance among French engineers until after the Courrieres disaster of 1906.

EXPERIMENTS IN ENGLAND BETWEEN 1850 AND 1885.

In 1870 Mr. William Galloway, former government inspector in Scotland, and then in charge of mines in Wales, began a special study of colliery explosions. He had observed that all the great explosions in Wales had occurred in dry and dusty mines; also the only great explosion in Scotland had occurred in the only dry mine in Scotland known to him. In 1875 he commenced a series of coal-dust experiments in a long box or miniature gallery, and on March 2, 1876, read a paper before the Royal Society in which he stated that "if coal

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[a] Second Rept. Roy. Comm., 1894, p. 5.

dust and air did not form an inflammable mixture a small addition of fire damp, which would not be inflammable alone, would become inflammable when coal dust is added."

In 1878 Prof. A. Freire-Marreco gave an account[a] of coal-dust experiments made in conjunction with Mr. W. Cochrane and Mr. Morison. They employed a box 8 feet long with a longitudinal partition, with a circulating current of air actuated by a fan. They arrived at the same general conclusions as Mr. Galloway.

Soon after making the experiments mentioned, Mr. Galloway investigated an explosion that occurred in the Llan colliery, South Wales, December, 1875, and reported that "coal dust had undoubtedly played the most important part in the explosion." Subsequently Mr. Galloway made further experiments and investigated the explosions at Pen-y-graig, Risca, and Seaham in 1880, and as a result decided "that fire damp is altogether unnecessary for the propagation of flame with explosive effect by a mixture of dry coal dust and air."[b]

Mr. Henry Hall, English mines inspector, in 1876 made experiments at St. Helens in an adit or drift which ran in from the outcrop of a coal seam and which was 135 feet long. Coal dust was laid on the floor and shots were fired at the face of the adit. Mr. Hall stated in a paper read before the North of England Institute of Mining and Mechanical Engineers that "flame traveled the length of the adit." The blast was very fierce "and would certainly have proved fatal to anyone struck by it in its course."

This was the first large-scale test of coal dust undertaken, but it appears to have been received with skepticism at the time. The prevailing impression was that some fire damp must have been present.

Up to 1880 the theory of the explosiveness of coal dust had made little progress. The British accidents in mines commission began its sittings in 1879, but did not make its final report until 1886. In a preliminary report issued in 1881 the evidence of practically all the expert mining witnesses, except that of Mr. Hall and Mr. Galloway, was to the effect that it was improbable that coal dust would do more than increase the range of a fire-damp explosion. Even Mr. Galloway testified (March 18, 1880) that it was necessary to have a slight amount of gas present to explode coal dust.

On September 8, 1880, a terrible explosion occurred at the Seaham mine, County of Durham, England, which attracted general attention to the subject of coal dust. Prof. Frederick Abel was commissioned to make some experiments with coal dust. His experimental

[a] Trans. North of England Inst. Min. and Mech. Eng., vol. 28, p. 85.
[b] Second Rept. Roy. Comm., 1894, p. 5.

apparatus, a long, narrow explosion box or flue, was similar to that of Galloway's. In his report he said:[a]

In the complete absence of fire damp, coal dust exhibits some tendency to become inflamed when passing a very large lamp flame at a very high velocity. If exposed to the action of a large volume of flame, as from the explosion of gunpowder, it exhibits a decided tendency to propagate flame. But so far as can be determined by experiments on a moderate scale, this tendency is of a limited nature.

Professor Abel, in giving evidence at the Seaham inquest, said that "if coal dust alone would have exploded every colliery would have been wrecked long ago."[b]

The Chesterfield and Derbyshire Institute of Engineers appointed a committee in 1880 to conduct some experiments with coal dust. The committee included Professor Marreco and Mr. Morison. The experiments were made in a miniature gallery 82 feet long, 16 inches wide, and 18 inches deep, connected with a chimney to produce an air current. Coal dust was introduced at the open end of the chamber and carried in by the current. A horse pistol was used to simulate a blown-out shot. The charge was one-half ounce of gunpowder. It was fired into the open end. Out of 134 tests with coal dust alone, ignition was obtained in 36 cases. Even when 6 per cent of gas was tried, no violent explosion resulted. In the opinion of the observers it was more of an inflammation than an explosion.[c]

The dust for these experiments was gathered from the floor, timber, and sides, and in all probability was more or less mixed with stone dust. This may have been the cause of the inconsistency in the results.

In 1884 Mr. William Galloway took a more positive stand than in April, 1879, when he appeared before the accidents in mines commission. In his fifth paper on the subject of coal dust, communicated to the Royal Society in May, 1884,[d] he states that no earlier author than himself had credited coal dust with being a principal factor in mine explosions, relegating fire damp to a secondary place.

EXPERIMENTS IN PRUSSIA.

The Prussian fire-damp commission in 1884 conducted a series of experiments with coal dust and with coal dust with gas in a gallery which had been built at the Koenig mine at Neunkirchen, Saarbrucken. This gallery was partly constructed under a refuse pile. It was 51 meters (167 feet) long and elliptical in cross section, 1.72 meters (5.6 feet) high by 1.20 meters (3.9 feet) wide. Twenty-eight varieties of coal dust were tested and compared, each separately tried

[a] Final Rept. Accidents in Mines Comm., 1886, p. 159.
[b] Blue book on Seaham colliery explosion, 1881, p. 146.
[c] Trans. Chesterfield and Derbyshire Inst. Eng., vol. 10, 1882.
[d] Proc. Roy. Soc. London, vol. 37, 1884, p. 42.

by placing about 15 kilograms (3.3 pounds) of it along 10 meters (32.8 feet) of the gallery. Several means were tried of distributing the dust, but scattering on the floor was practically as efficient as any other way. The igniting charge consisted of 230 grams (0.51 pound) of black powder placed in one of several cast-iron blocks or cannons at the inner end of the gallery. Clay and coal dust were separately used for tamping the shot. With clay for tamping, the flame from the explosive itself was 3 to 4 meters (6½ to 10 feet) long, but with the coal tamping it was from 9 to 16 meters (30 to 52½ feet) long. The coal used in each test was analyzed and the resultant coke was also analyzed. In one instance the volatile matter was reduced from 21.8 to 13.6 per cent.

The conclusion of the commission was as follows:[a]

1. The presence of coal dust with or without small quantities of fire damp always increases the length of a blown-out shot.

2. When fire damp is fully absent, the prolongation is usually limited, not exceeding 6 to 15 meters for most varieties of dust, when clay tamping is used and when the sides of the bore hole do not themselves yield coal dust and gas, or 9 to 21 meters when dust is used for tamping or is produced from the hole itself. But there are coal dusts which, once ignited by a shot, burn or spontaneously give flame far beyond the locality strewn with the dust, and sometimes actually produce explosions when no fire damp is traced.

The conclusions drawn by Mr. Hilt, a member of the Prussian commission, were submitted to the British commission as follows:[b]

1. The presence of coal dust in more or less abundance in the immediate vicinity of the working face gives rise to more or less considerable elongation of the flame projected by a blown-out shot, whether small quantities of fire damp be present in the surrounding air or not.

2 (*a*) In the complete absence of fire damp the elongation or propagation of flame is generally of limited extent, however far the deposits of dust may extend in the mine ways.

(*b*) There are, however, certain descriptions of coal dust which, if ignited by a blown-out shot, will not only continue to carry on the flame, even to distances extending considerably beyond the confines of the dust deposits, but will also give rise to explosive phenomena or results, in the complete absence of any trace of fire damp, which in character and effects are similar to those produced with some other dust in air containing 7 per cent of fire damp.

3 (*a*) All the phenomena produced by the burning of, and propagation of flame by, coal dust are intensified by the presence in the air of small proportions of fire damp, but such dusts as will per se only favor to a limited extent the propagation of flame from a blown-out shot, give rise only to moderately increased volumes of flame, in the presence of even as much as 3 per cent of gas, and are not at all capable, under those conditions, of carrying on flame throughout the length of a dust-strewn area; the latter result will, however, be produced, even with such dusts, if the proportion of fire damp in the air amounts to 4 per cent.

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[a] Rept. Prussian commission; Preuss. Zeitschr., vol. 32, 1884, 1885; also Eng. and Min. Jour., 1885, p. 221; also Trans. Am. Inst. Min. Eng., vol. 24, 1895, p. 901.

[b] Final Rept. Accidents in Mines Comm., 1886, p. 43.

According to the evidence given by Mr. William Galloway before the British royal commission in 1891, the Prussian investigators obtained inconsistent results when they attempted to classify dusts in the order of their relative explosibility. He said:[a]

One of the dusts which they described as nonexplosive came from a colliery called Camphausen and they named it as quite a safe dust. Shortly afterwards an exceedingly violent explosion occurred at Camphausen colliery killing some 200 men, and the government director of mines in the district wrote to me immediately afterwards stating that the mines were so entirely free from fire damp that he could come to no other conclusion but that coal dust had been the sole cause of that explosion. * * * It is a remarkable and noteworthy fact that the degree of explosiveness of the coal dust with which the members of the Prussian commission made their experiments appeared to be directly in proportion to the fineness of the dust, and to have little or no connection with their chemical composition. * * * I may state my own conviction that the finest dust of all kinds of coal, with the exception possibly of the dryest kinds of anthracite, is inflammable or explosive when mixed with air and ignited in large volumes.

As a further result of their tests, the Prussian commission declared that black powder and all other slow explosives ought to be prohibited in collieries containing fire damp, and that even dynamite and other high explosives, though permissible in certain cases, ought not to be used where accumulations of fire damp are possible in sufficient quantity to give a clearly perceptible blue cap on a lamp; and that in all cases it is desirable that the air should be tested within a radius of 10 yards before igniting any shot. In consequence of this report, shot firing was prohibited altogether in mines controlled by the Prussian Government, where safety lamps were used.[b]

It is evident that by 1886 the serious danger of coal dust was realized in Germany, although the investigators were not quite ready to believe that coal dust would explode without fire damp being present. In another part of Germany, at Zwickau in Saxony, a testing gallery had already been erected (1883), and thenceforward, investigations in various parts of Germany went on more or less continuously, both under government supervision and by various mining companies.

EXPERIMENTS IN AUSTRIA BETWEEN 1885 AND 1891.

In Austria a commission on explosions in mines was appointed in 1885, and in 1886 a testing gallery was established at Mährisch-Ostrau. A large number of experiments were conducted and in 1891 the Austrian commission made its report, the substance of which is stated by the British royal commission as follows:[c]

In all, 353 experiments were made with 345 kinds of dust, generally without any admixture of gas. These experiments showed that, without any admixture of fire

[a] First Rept. Roy. Comm. on Mines, 1891, p. 36.
[b] Trans. Am. Inst. Min. Eng., 1894, vol. 24, p. 902.
[c] Second Rept. Roy. Comm., 1894, p. 8.

damp, nearly all kinds of coal dust were ignited by a cartridge of 100 grams of dynamite lying loose; while many notoriously dangerous dusts were less inflammable than other inflammable dusts. It was further shown that a small admixture of fire damp notably increased the danger and sensitiveness of coal dust, so that a dust which is otherwise not dangerous may give rise to a disastrous explosion if there is a little fire damp present. The fineness of the dust, as well as its dryness, greatly increases its sensitiveness and danger.

VIEWS OF ENGLISH AUTHORITIES BETWEEN 1886 AND 1908.

On March 15, 1886, the British accidents in mines commission, which had been sitting since 1879, after reviewing the coal-dust problem and experiments made in England and other countries, reported the following facts as conclusively established:[a]

(1) The occurrence of a blown-out shot in working places where very highly inflammable coal dust exists in great abundance may, even in the total absence of fire damp, possibly give rise to violent explosions, or at any rate be followed by the propagation of flame through very considerable areas, and even by the communication of flame to distant parts of the workings where explosive gas mixtures, or dust deposits in association with nonexplosive gas mixtures, exist.

(2) The occurrence of a blown-out shot in localities where only small proportions of fire damp exist in the air, in the presence of even comparatively slightly inflammable, or actually noninflammable, but very fine, dry, and porous dusts, may give rise to explosions, the flame from which may reach to distant localities where either gas accumulations or deposits of inflammable coal dust may be inflamed, and may extend the disastrous results to other regions.

It will be observed that this report shows a great change of sentiment from the time of the preliminary report in 1881, when the commission considered the explosibility of coal dust of itself as improbable.

In the same year W. N. and J. B. Atkinson published a book entitled "Explosions in Coal Mines," in which they made a special study of five then recent English explosions and reviewed the history of past explosions. They state, in unqualified language, that coal dust was the effective agent in most of the great mine explosions.

The reports of the accidents in mines commission in 1886, and of other investigations, led to an enactment by Parliament in 1887 requiring certain precautionary measures to be used in dusty mines, as follows:

If the place where a shot is to be fired is dry and dusty, then the shot shall not be fired, unless one of the following conditions is observed, that is to say: (1) Unless the place of firing and all contiguous accessible places within a radius of 20 yards are at the time of firing in a wet state from thorough watering or other treatment equivalent to watering, in all parts where dust is lodged, whether roof, floor or sides; or (2) in the case of places in which the watering would injure the roof or floor, unless the explosive is so used with water or other contrivance as to prevent it from inflaming gas or dust, or is of such a nature that it can not inflame gas or dust.

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[a] Final Rept. Accidents in Mines Comm., 1886, p. 48.

Despite the foregoing affirmative report by the royal commission, there was not a general acceptance among mining men of the explosibility of coal dust in itself, so that in 1890 Mr. Henry Hall, government inspector of mines, was commissioned to make some further experiments on a large scale in certain disused shafts with coal dust from various mines.

Some of these tests were very spectacular, notably several at the Big Lady pit, which was 630 feet deep and was connected by a small arched way with another shaft. The experimental shaft was the upcast. The firing charge was $1\frac{1}{2}$ pounds of black powder in a cannon placed 540 feet from the surface. In the seventh test—

dust was ignited, followed by a continuous roar, and a rush of flame completely filled the pit mouth and ascended 60 feet into the air. This was the most violent explosion since the commencement of the experiment. It is difficult for anyone who did not witness this experiment to realize the extent of the explosion. The flame continued to issue from the pit for five to six seconds, followed by dense smoke. The violence carried away some of the woodwork 37 feet above the pit mouth.[a]

Mr. Hall, in his summary, states:[a]

These experiments conclusively prove that blasting with gunpowder in dry and dusty mines may cause serious disasters *in the entire absence of fire damp.* It is impossible to explain why many of the experiments failed to cause explosions or to ignite the dust, but the fact that at intervals these did occur perfectly justifies the above conclusion.

In February, 1891, a royal commission on explosions from coal dust in mines was appointed, and began hearing evidence in the following month. Its first report of evidence, without conclusions, was published in July, 1891. In 1892 its sittings were adjourned, pending further experiments by Mr. Henry Hall, which were conducted at intervals in that year and in 1893.

The commission made its second report in 1894, giving additional evidence and their final conclusions. In reviewing the evidence they state:[b]

The experiments made by Mr. H. Hall in 1890, 1892, and 1893 on a larger scale, and in shafts of mines, appear to be conclusive in the same sense, although they show that an explosion is not a certain consequence of every shot that blows out or emits flame, but depends on many circumstances affecting the condition and quantity of the dust, the nature and strength of the explosive, the size of the galleries or shafts, etc.

The Prussian commissioners reported that "if absolute immunity from blown-out shots could be obtained, the dangers which are brought about by coal dust would be almost entirely prevented." In their experiments they found that no shots, other than a blown-out shot, caused an explosion of the dust.

It is, however, the opinion of several witnesses that the danger is not confined to blown-out shots, but that an overcharged shot which does not blow out, or one which partially does the work for which it is intended, may exhibit flame and therefore ignite the dust. In the opinion of Mr. W. N. Atkinson, the explosions at Seaham in 1871 and 1880, at Elemore, at Usworth, and at Altofts were caused by shots which did not blow out.

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[a] First Rept. Roy. Comm., 1891, p. 153. [b] Second Rept. Roy. Comm., 1894, p. 11.

The royal commission summarized their conclusions in the following words: [a]

(1) The danger of explosion in a mine in which gas exists, even in very small quantities, is greatly increased by the presence of coal dust. (2) A gas explosion in a fiery mine may be intensified and carried on indefinitely by coal dust raised by the explosion itself. (3) Coal dust alone, without the presence of any gas at all, may cause a dangerous explosion if ignited by a blown-out shot or violent inflammation. To produce such a result, however, the conditions must be exceptional, and are only likely to be produced on rare occasions. (4) Different dusts are inflammable, and consequently dangerous, in varying degrees; but it can not be said with absolute certainty that any dust is entirely free from risk. (5) There appears to be no probability that a dangerous explosion of coal dust alone could ever be produced in a mine by a naked light or ordinary flame.

By the time the royal commission had issued this final report, in 1894, the mining experts in England had became very generally convinced that coal dust was not only a factor, but the most important element in the great explosions occurring in collieries, and thereafter the experiments and investigations were directed to remedies. In 1896 a coal-mine regulation act was passed by which power was given to the secretary of state to prohibit the use of dangerous explosives. This necessitated the testing of explosives used in mines, and to this end a testing station with necessary apparatus was erected at Woolwich and opened for testing June 5, 1897. As an explosive mixture of gas is more sensitive than coal dust, it was reasoned that an explosive that will not ignite gas would not ignite coal dust, hence the apparatus was designed primarily to determine the relative liability of the various explosives to ignite an explosive gas mixture.

GERMAN, FRENCH, AND BELGIAN STATIONS FOR TESTING EXPLOSIVES.

In Germany the education of the mining public to the danger of coal dust had gone on simultaneously with that in England. In 1894 a station for testing mine explosives in the presence of dust and gas mixtures was established at Gelsenkirchen in Westphalia by the mine operators and placed under the supervision of a government engineer. The testing gallery is 34 meters long. In cross section it is elliptical, 1.80 meters (5.9 feet) high and 1.35 meters (4.4 feet) wide. This gallery and the other apparatus for testing the explosives, also apparatus for testing safety lamps, mine motors, etc., have been in continuous use since the establishment of the station.

A similar station was established by the Belgian Government at Frameries, and the same general methods of testing explosives in the presence of gas and coal dust are used for the formation of a Belgian "permitted" list.

[a] Second Rept. Roy. Comm., 1894, p. 24.

In France, as already mentioned, the effect of the early investigation, and particularly of the French fire-damp commission, was to prevent acceptance of the theory of the explosiveness of coal dust when fire damp was not present. The effort of the French engineers was to prevent ignition of fire damp, and every precaution was taken in the French mines to this end. It was felt that if this danger could be guarded against, that there was practically no danger from coal dust. Captain Desborough, of England, in a "Report on bobbinite" (1907), states:

> The French were, I believe, the pioneers in placing restrictions upon the indiscriminate use of explosives in gassy mines. After many valuable experiments had been carried out on a laboratory scale, it was decided that in gassy mines no explosives should be used whose calculated theoretical temperature of explosion exceeded 1,500° C., which is considerably above the ignition point of a fire damp and air mixture.

The general good care exercised in the mines of France and the excellent ventilation gave France comparative freedom from the large mine disasters that were occurring in other countries, until the terrible disaster at the Courrières mines in 1906. Although there was no official French report attributing the cause to coal dust, such was the opinion of the English investigators, Sir Henry Cunynghame and Mr. W. N. Atkinson, who examined the mine. They ascribe the initial cause to a blown-out shot in a heading, igniting coal dust, and state further that the propagation through the mine was probably through the agency of coal dust.[a]

As a result of the disaster the central committee of mines of France (comité central des houillères de France) established a station at Liévin, in the Pas de Calais district, in 1907 for the study of the relative explosibility of different coal dusts with various percentages of fire damp and without fire damp. A small-scale experimental gallery was first erected to determine on plans for a large-size gallery. After a series of tests with the former, the large permanent gallery, or the first section of it, was erected in 1908. As at the other European stations there is no difficulty in causing explosions of coal dust without the presence of fire damp, at will, by discharging either black powder or dynamite from a cannon at one end of the gallery.

Some of the conclusions of M. Taffanel, the government engineer in charge of this station, are given in subsequent pages of this report (pp. 43–44). The plans are to gradually extend this gallery to a length of 500 meters and to investigate means for preventing or of limiting the explosion of coal dust.

The results already reached by the Liévin station and by the testing stations of other countries have fully convinced the French engineers of the dangers of coal dust.

[a] Home Office report on Courrières disaster, p. 11.

ALTOFTS GALLERY, ENGLAND, 1908.

In England a new royal commission on mines was appointed in 1906, which began hearing evidence in June of that year. This commission, while taking up all questions relating to mines, has given a great deal of attention to coal dust and remedial methods. It has issued four volumes of evidence, one in 1907, two in 1908, and one in 1909, in which many methods for solving the coal-dust question have been suggested.

The general interest in the subject led the Mining Association of Great Britain to establish in 1908 a testing gallery of unusual dimensions at the Altofts colliery in Yorkshire. It is 7½ feet in diameter and about 900 feet long, with several right-angle turns. It is built of ⅜-inch boiler plate. A concrete floor extends through it, also a pit car track. Unlike the other galleries, the prime purpose is not the testing of explosives, but the study of the behavior of coal dust in exploding. The first tests were to demonstrate and convince the few who still had doubt as to the explosibility of coal dust. Some of the explosions produced were very violent. In one case, where a longer portion (450 feet) of the gallery had been charged with coal dust than before or since, the resulting explosion tore off the two end sections, threw one heavy piece of boiler plate several hundred feet, blew out windows in houses for a mile or so around, and it is claimed produced a concussion that was felt 7 miles away.

After a series of preliminary demonstrations, the study of remedial methods has been taken up. Two plans have been tried: Having an intercepting zone free from coal dust, and the employment of a zone of stone dust. These will be discussed under other heads (pp. 80–83).

SECOND REPORT OF ROYAL COMMISSION ON MINES, 1909.

The second report of the royal commission on mines appeared in September, 1909. The coal-dust question is discussed as well as other dangers, and with regard to dust the commission says:[a]

> The witnesses, who included those best qualified from scientific or practical experience to speak on the question, expressed opinions which were often widely divergent, as to the best means of meeting the danger of explosions, but they were generally agreed on two points—that coal dust is liable to explosion with or without the presence of fire damp, under conditions which are at present to be found in most coal mines in this country and abroad, and that there is pressing need for the elucidation of the problems involved by a series of exhaustive experiments on an adequate scale. With regard to the first point, it was a matter of satisfaction to us that all the witnesses whom we consulted expressed themselves as adherent to the received opinion on the subject of coal dust. In this respect we found ourselves in a better position than the commission who preceded us—the royal commission on accidents in mines (1879–1886) and

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[a] Second Rept. Roy. Comm. on Mines, 1909.

the royal commission on coal dust (1891–1894) in that *we were able to confine our attention to the means of dealing with coal dust without having to prove the necessity for such means.* * * * We do not mean to convey the impression that all managers and mining engineers are fully alive to the danger of coal dust. Unfortunately, recent occurrences have tended to show that this is not the case. If such is the position taken by some managers in this country, it is the less surprising that the workmen do not all appreciate the danger of coal dust.

The commission, after speaking of the merits of the Altofts gallery, the thoroughness of its equipment, and methods in carrying on the tests, say:

Until these experiments are completed we are unable to make recommendation covering the whole question of the means of preventing coal-dust explosions.

Figures are quoted from the British "Annual Report on Mines and Quarries" by five-year periods, of the death rates from accidents underground in mines per thousand persons employed. The annual death rate due to explosions of fire damp or coal dust shows a regular decrease from the period 1851–1855, when it was 1.280 per 1,000, until 1907, when it was 0.057. In other words, considering an equal number employed, for 22 men killed in 1851–1855 by fire damp or coal dust, but 1 was killed in 1907.

RECENT AUSTRIAN EXPERIMENTS.

The Vienna permanent fire-damp committee in 1908 decided to continue experiments begun some years before with coal dust in its gallery at Babitz, near Segengottes in the Rositz district, Austria. This gallery consists of part of an old mine level 293.7 meters (964 feet) in length, connected with the surface by three shallow shafts. Coal dust is introduced sometimes on shelves and sometimes through pipes leading from the surface, the dust being thrown into suspension by fans. The coal dust is distributed for a distance of 10 to 90 meters (33 to 295 feet) from one end, where there is an explosion chamber. The dust is ignited by blow-out shots from a cannon or cannons charged with black powder, or by dynamite cartridges hung in the explosion chamber. The flame, in these experiments, traveled from 50 to 180 feet beyond where the coal dust was laid, depending upon the character of the dust, its purity, its fineness, and its dryness. These experiments are still continuing, and as yet no conclusions have been reached.

A description of this station is given in the Colliery Guardian for September 24 (p. 635) and October 1 (p. 687), 1909.

HISTORICAL REVIEW OF THE COAL-DUST QUESTION IN THE UNITED STATES.

GRAHAMITE EXPLOSIONS IN WEST VIRGINIA, 1871–1873.

One of the earliest recorded dust explosions in the United States was in a grahamite mine in Ritchie County, W. Va., on February 9, 1871, when 4 men were killed as the result of a very violent explosion. The official report of the investigators was that an "explosion of powder (18½ cubic inches in the shot) pulverized a certain quantity of mineral (grahamite—a hydrocarbon) and in that state it was easiest decomposed. The indications are that gas burned along all the air passages and exploded at the portal."[a]

The management subsequently employed sprinklers, as much dust was made in running the mined mineral through chutes, but a second explosion, February 25, 1873, also from shot firing, killed 4 men.

FLOUR-MILL EXPLOSION AT MINNEAPOLIS, 1878.

On May 2, 1878, a tremendous explosion occurred in the Washburn Flour Mills, at Minneapolis, completely wrecking the building and setting on fire 6 other flouring mills and a number of other buildings. Professors Peckham and Peck were commissioned by the coroner's jury to investigate. They made experiments in closed boxes with a variety of powdered substances to test their explosibility. Among other things, they tested various flour mixtures and coal dust. The powdered materials were blown into the box by bellows and ignited by an open light. The findings of Professors Peckham and Peck were to the effect that practically all finely divided highly carbonaceous material would explode under the conditions tried. Their report was not made public at the time, but was published in issues of the Chemical Engineer, March, April, and May, 1908. An abstract of it appeared in Mines and Minerals for September, 1908, page 55.

In an issue of the Scientific American Supplement, May 25, 1878 (p. 1985), there was an article entitled "Dust as an explosive." After a general discussion of the subject, it continues:

> It has been well known for a long time past that it is not alone to mixtures of the issuing gases with air that the explosions in colleries are to be ascribed. Finely divided coal is always present to a more or less extent in the air of a mine, or, if not present in sufficient quantity, is sure to be produced by the shock of an explosion. This dust furnishes a material which gives the fire power to spread from gallery to gallery should the mixed gases themselves be insufficient in quantity to permit such a spread. Indeed, it would appear that coal dust itself, when mixed with certain proportions of air, renders the air explosive without the presence of any of the gases usually evolved in coal mines; and there can be no doubt that the presence of coal dust renders mixtures of coal mine gas and air explosive that would otherwise be quite harmless.

[a] Trans. Am. Inst. Min. Eng., vol. 24, 1894, p. 195.

Then follow remarks about the Haswell mine explosion report of Lyell and Faraday, and some quotation from Galloway's papers. In view of the definite statements in this article, it is surprising how delayed the general acceptance of the coal-dust theory was in this country.

EXPLOSION AT POCAHONTAS MINE, WEST VIRGINIA, 1884.

On March 13, 1884, occurred the first great mine explosion of the bituminous fields of this country, at the Pocahontas mine, West Virginia. There were 114 men killed, all who were in the mine. At the request of the operating company, a committee was appointed by the American Institute of Mining Engineers, consisting of Messrs. J. H. Bramwell, Stuart M. Buck, and Edward H. Williams, jr. As soon as the mine workings were accessible, they made a careful examination of them. A summary of contributing causes found by them is as follows:[a]

1. The unusual dryness of the mine.
2. The very large quantity of dust in an extremely fine state of division.
3. The constant working of the mine day and night, allowing no time for clearing air [of powder smoke].
4. The use of excessive quantities of powder, largely increasing the amount of dust.
5. The probable existence of small quantities of fire damp slowly given off from the coal.
6. The employment of incompetent and inexperienced men.
7. The almost complete stagnation of the air on the east side of the entry, owing to the fact that the main doors were untended and fastened open, allowing the air to pass up the main entry direct to the fan.
8. The failure to recognize and appreciate the previous warnings of danger given by occasional flashings of unusual extent, when shots were fired, indicating the need of special precaution.

The investigators say further: "The existence of fire damp is a disputed point." They obtained no evidence of the previous existence of fire damp from the workmen of the other shifts, except that a miner claimed that once, when his light was in an undercutting, he observed a lengthening of the flame. The investigators comment that in general the evidence given by the former workers appeared to be prejudiced and therefore unreliable.

On reopening the mine after the explosion and partial flooding, no trace of fire damp was discovered, and none showed at the time of inspection, although the ventilation had been only partly restored, especially to the rise.

Their conclusion was:

We believe that the explosion was due mainly to dust, and that it originated either in the (3d) east headings ("at D") or very possibly in one of the rooms ("south of D"—south of the 3d east headings). The evidence of a short northward current being obliterated by the stronger reaction from the close heading. We can not determine the initial cause, whether a blast or the accidental ignition of a small accumulation of fire damp.

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[a] Trans. Am. Inst. Min. Eng., vol. 13, p. 237.

It may be stated that after the mine was reopened fire damp was not detected in subsequent operations.

For some years after the Pocohontas explosion, the coal-dust problem attracted little attention in this country, and operating men were content to await the results of experimenting abroad. Each was chiefly concerned in his own part in the tremendous development going on in the various great bituminous fields of the country. There was an awakening of interest in coal dust when explosions began to occur in mines in parts of the western region of the interior coal province, particularly in Iowa. Many of these explosions were in shallow mines in which fire damp had never been found before the explosions and was not found after them. The Iowa coal is neither gassy nor coking in the ordinary sense; it is high in ash, and carries from 12 to 14 per cent of moisture when freshly mined.

EXPLOSION AT PEKAY MINE, IOWA, 1892.

The first of the Iowa explosions occurred at the Pekay mine, February, 1892. Fortunately it was on a holiday, and only 4 men were in the mine. Three of these were killed, but the fourth, who was in a mine stable near the hoisting shaft and out of range of the explosion, escaped. The writer examined the mine on the morning following the explosion. Much violence was manifested through several pairs of entries and the main entries on one side. The fan was partly wrecked. The mine was dry and dusty. Coked particles were not observed, but there was burned dust and the flames had ignited kegs of powder at different points in the mine. No fire damp had ever been found in the mine and none was found after the explosion. The evidence indicated that the explosion had begun in a certain room where three greatly overcharged shots had been discharged at or about the same time, throwing out to a distance a large mass of coal. No undercutting nor shearing had been done. What was termed "blasting off the solid" was then being introduced in Iowa. In the opinion of the writer, the flame of the shots ignited coal dust, which propagated the explosion throughout the mine.[a]

Shortly after this explosion several others occurred in Iowa, at the Cedar mine and elsewhere. These were also ascribed to either blown-out or overcharged shots "on the solid." Similar explosions, generally on a small scale, because the conditions were unfavorable for widespread explosions, occurred in the fields of southeast Kansas, also remarkably free from fire damp, and in the McAlester field of Indian Territory (now Oklahoma), where, however, the situation was complicated by the presence of more or less gas.

[a] Rice, G. S., The Pekay explosion: Trans. Illinois Min. Inst., vol. 2, 1893.

PROPOSED REMEDIES FOR DUST.

The numerous accidents of this nature naturally led to a great deal of anxiety in the interior fields, and a great many palliatives were suggested and in some cases tried. There was considerable belief in the explosibility of coal dust, and, as it was noted that the explosions were usually more severe on the intake air way, it was proposed, and in some States was carried out under the instructions of the mining departments, that the fan should be slowed up or stopped at the shot-firing time. This was on the theory that fresh air and pressure increased the chance of ignition. To a small extent, sprinkling or wetting the floors of the roads from a tank car once or twice a week was practised.

An important change was then made in many of the States west of the Mississippi by the passage of laws requiring the shot firing to be done by shot firers, the miner still drilling and charging the drill holes. The immediate results were not at all favorable, as the miners, relieved of personal risk, transferred it to the shot firers. There was an increasing tendency to do less and less cutting to relieve the shot, and to increase the already large charges of black powder. The effect was to cause more accidents from blown-out and overcharged shots, although the number of killed and injured men was decreased, owing to the fewer number of men exposed to the hazard. Further legislation followed in some States, compelling the inspection of holes by the shot firers before they were loaded by the miner. This measure very much improved the situation, resulting in a smaller number of killed and injured from shot firing.

RESULTS OF SHOOTING OFF THE SOLID.

East of Mississippi River, in the eastern region of the interior coal province, the number killed from mine explosions was relatively very small until a change came in the method of paying the miners, in 1897. Before that time the miners had been paid on the basis of the amount of lump or screened coal produced. After 1897 they were paid on the basis of the amount of run-of-mine coal produced. This took away from the miner the incentive for cutting the coal and for using small charges of powder, and put a premium upon shooting down the coal in the cheapest and easiest manner. "Shooting off the solid," theretofore practiced only to a small extent, became very general, and with it a large increase in the amount of black powder used in the shots. As in the coal-mining States west of the Mississippi, this produced an immediate increase in the number of explosions and fatalities therefrom. Fortunately, the explosions were usually of limited character, because the natural conditions were unfavorable to wide-spread explosions. Nevertheless, the accidents were so frequent that legislation followed in Illinois requiring the employment of shot firers[a] and inspection by them of the drill holes, and limiting the charge of black powder. The amount of powder used in a shot was difficult to control, and in some mines in Illinois the output of coal per keg (25 pounds) of powder fell as low as 15 tons (of 2,000 pounds).

In the meantime mines opened in the deeper-seated coals in southern Illinois found considerable gas (methane). Even where the coal was undercut by machine, overcharges of powder were frequently used, so that serious accidents resulted, in which some or all the shot firers were killed. This condition still prevails (1909), but more care is now exercised by the shot firers in condemning bad holes, and a considerable number of operators are paying more attention to dampening coal dust along the entries by sprinkling.

In Indiana the conditions have been somewhat similar to those in Illinois, except that the employment of shot firers has not been compulsory, so that explosions killing a considerable number of miners have occurred, notably at Princeton. Very large charges of black powder are used in the Indiana mines. The revised state act of 1907 fixed the limit at 6 pounds of black powder, but instances have been reported in which as much as 10 to 12 pounds of powder has been used in a single shot. Where law and local regulations allow 25-pound cans of powder to be in possession of the miner in the mine, and allow him to charge and fire his shots, there is no way of effective control to insure safe conditions.

In Pennsylvania, the chief coal-producing State of the country, and in Ohio the method of paying the miner on the screened-coal basis has prevailed to the present time; and in these States and in parts of West Virginia the system of undercutting before shooting has generally been adhered to except in the Connellsville coke region.

GREAT DISASTERS OF 1907.

Though numerous explosions occurred in the Appalachian field in Virginia, West Virginia, and Pennsylvania up to 1907, the only ones of the most disastrous order were those at Newburg, W. Va., in January, 1886, Red Ash, W. Va., in 1900, Johnstown, Pa., in July, 1903, Cheswick, Pa., in January, 1904, and Pocahontas, Va., in 1906, and in the majority, including those cited, there was always a question whether fire damp was not the initial cause. However, in the propagation through the mine there is little question but that coal dust was the chief factor. The same might be said of the explosions that occurred from time to time in Alabama and Tennessee.

In 1907 occurred an appalling series of great wide-sweeping disasters. On January 23, at the Primero mine, Colorado, there were 24

[a] In mines where in shooting more than 2 pounds of black powder is used in any one shot.

deaths; on January 26, at the Penco mine, W. Va., 12 deaths; on January 29, at the Stuart mine, near Fayetteville, W. Va., 90 deaths; on February 4, at the Thomas mine, Thomas, W. Va., 25 deaths; on December 1, at the Naomi mine, Pa., 35 deaths; on December 6, at Monongah mines Nos. 6 and 8, W. Va., occurred the greatest disaster in the history of coal mining in the United States, 358 lives having been lost; on December 16, at the Yolande mine, Ala., 56 men were killed, and on December 19, at the Darr mine, Pa., 230 men were killed. In this black month of December 648 men were sacrificed chiefly from the effects of coal dust, which, if not the initial cause, in all cases was the agent carrying death. Including the powder explosions and so-called "windy shots," there were 1,148 men killed by mine explosions in the United States during 1907.[a]

INACCURATE REPORTS OF ACCIDENTS.

Most of the so-called "powder explosions" and "windy shots" are in reality dust explosions. It is true that the origin of these is generally from blown-out or overcharged black-powder shots, but it is without question coal dust that carries the flame, and death in its trail. In certain States it is considered that legal responsibility attaches, if the fatality is pronounced due to coal dust; and this fact, together with the knowledge in many such instances that improper use of powder was the initial cause has led to the use of inexact and ambiguous terms in reports to the several state statistical bureaus.

FATALITIES IN 1908.

In 1908 the fatalities due to mine explosions of various kinds numbered 469, according to state statistics reported to Mr. E. W. Parker, of the United States Geological Survey.[b] This shows a marked improvement over the previous year.

INQUIRY BY UNITED STATES GEOLOGICAL SURVEY.

On June 10, 1907, the Secretary of the Interior transferred the supervision of the work of the coal-mine inspectors in New Mexico and Indian Territory (now included in the State of Oklahoma) to the United States Geological Survey. The Secretary suggested to the officers of the Survey that the general mining conditions in the Territories be investigated, with a view to lessening the number of mine accidents. Under the direction of J. A. Holmes, expert in charge of the technologic branch, an inquiry was begun into the nature and extent of coal-mine explosions and the methods employed to prevent them. In December, 1907, a brief summary of the results of this inquiry was published as Bulletin 333.

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[a] Mineral Resources U. S. for 1907, U. S. Geol. Survey, 1908, pt. 2, p. 58.
[b] Mineral Resources U. S. for 1908, U. S. Geol. Survey, 1909, pt. 2, p. 56.

The coal-dust question in this country can not be said to have awakened widespread interest among mining men until the terrible disasters of December, 1907. In response to a demand by those interested in coal mining throughout the country, Congress in 1908, made an appropriation for the investigation of mine explosions, which became available July 1, 1908. The United States Geological Survey was charged with the investigation. A testing station was at once decided upon and was established at Pittsburg, Pa. The station was officially opened December 3, 1908, and testing of nonflaming explosives was begun soon after. Field investigations of mine conditions and of mine explosions were carried on, especially of the explosions at Marianna, Pa., and Lick Branch, W. Va., in 1908; Rend, Ill., Wehrum, Pa., Eureka, Pa., Johnstown, Pa., and Herrin, Ill., in 1909; and Primero, Colo., Drakesboro, Ky., Stearns, Ky., Mulga, Ala., and Palos, Ala., in 1910. Special attention has been paid to the humidity of the mine air and the condition of the dust. At the Pittsburg testing station some experiments have been made with coal dust, described hereafter, and this work will be actively pursued in the future.

While it is probable that for several years the leading mining men in this country have believed in the explosibility of coal dust without the presence of fire damp, yet until the public demonstrations were given at the testing station at Pittsburg, during 1908–9, and reports were received of similar tests made abroad, a large proportion disbelieved. These tests were so convincing to those who saw them, and such general publicity has been given to them, that it is now exceptional to find a mining man who does not accept the evidence of the explosibility of coal dust. The question of the day no longer is "will coal dust explode?" but "What is the best method of preventing coal-dust explosions?"

COAL DUST AND ITS ORIGIN AND DISTRIBUTION.

DEFINITION OF DUST.

There is a diversity of opinion as to what the term "coal dust" means; that is, how finely must coal be divided to be termed dust. Some writers base the distinction on the point whether it can be carried to considerable distances by air currents. Coal that will pass through 100-mesh screens (100 wires to the linear inch) is frequently accepted as representing mine dust. For testing explosives at the Pittsburg station coal passed through 100-mesh is taken as standard. In the foreign galleries the practice varies between this size and coal that passes through 200-mesh.

For the consideration of coal dust as it effects mining, the writer proposes tentatively a definition based on the capacity of the dust to propagate flame in the incipient stages of an explosion, as determined at the Pittsburg station under the conditions hereafter stated. By this definition coal particles passing through a 20-mesh wire sieve (20 wires to the linear inch) will be termed dust. In the Pittsburg gallery tests only partial flame propagation was obtained under the prescribed conditions with coal that passed through the 20-mesh and remained on a 40-mesh sieve, but the partial propagation was sufficient to indicate that under slightly more severe conditions, namely, a larger initiating charge of black powder, the propagation might be complete. In fact, under the definition given, subsequent experiments may demonstrate that larger particles of coal than 20-mesh should be included.

IGNITION AND PROPAGATION.

Ignition of coal dust, as the term is applied by the writer to tests in the Pittsburg gallery, is an inflammation of the dust, caused by the flame of the explosive, with consequent extension of that flame more or less; and the term "propagation" is used for conditions in which the inflammation extends through and beyond the area in which coal dust has been laid along the shelves of the gallery, or beyond the area in which dust has been put into suspension by fans.

COAL-MINING METHODS AND DUST PRODUCTION.

Breaking down the coal at the face of the mine is done by one of the following methods: By undercutting in the underclay or coal itself and wedging, as in long-wall work; by undercutting or shearing by hand in the coal and blasting with light shots; by the same method with machines; and finally by "shooting off the solid."

Of the foregoing manifestly the long-wall system will produce much less coal dust than any of the other systems, and its general introduction in this country would probably very much lessen the number of dust explosions. The system has been little used in this country, partly because the natural conditions are not generally favorable, and, where they are, because it costs more to mine a ton of coal by this than by the more wasteful room-and-pillar system. However, one type of the long-wall system, the "retreating" long wall, is generally applicable and is the cheapest of all methods to work, but takes a large investment of capital. The Wilmington and Third Vein fields of northern Illinois, in which the natural conditions allow the use of "advancing long wall," comprise the only important long-wall district in the country, having an output of 5,000,000 to 6,000,000 tons annually. No explosion has ever occurred in this field.

As between the methods of mining the coal at the face in room-and-pillar work—"shooting off the solid," and cutting the coal by hand or machine and then shooting—we have no authoritative figures as to their relative production of dust.

DUST FROM HAND AND FROM MACHINE UNDERCUTTING.

In the process of cutting coal by hand and by different types of machines, some tests have been made by private interests and their results made public.

Tests of the production of dust in undercutting by hand, by chain machines, and by air punching machines in the Pittsburg seam were made by the late B. F. Jones. Mr. Jones published his results in the March, 1908, issue of Mines and Minerals (p. 397). The tests were made in three adjacent "butt" rooms in the Westmoreland mine, Pennsylvania. The undercutting by each process was conducted in a separate room, and in each case was 4 feet 3 inches deep and as wide as the room (15 feet). The height of undercutting with the puncher was 11 inches at the front and 3 inches at the back, and with the chain machine 4 to 4½ inches throughout. The seam was 6 feet thick.

The same total amount of coal was assumed to have been produced from each room (15.68 tons of 2,000 pounds). The results, reduced to tabular form, are as follows:

Weight of cuttings and percentage of total coal mined by different methods, as determined in experiments at Westmoreland mine, Pennsylvania.

Method.	Total cuttings.		Cuttings passed through 16-mesh.		Cuttings passed through 40-mesh.	
	Pounds.	Per cent.	Pounds.	Per cent.	Pounds.	Per cent.
Puncher	3,436	10.95	755	2.40	394	1.250
Chain machine	1,836	5.86	333	1.06	155	.494
Hand pick	4,533	14.45	349	1.11	128	.408

Evidently these figures did not include the dust produced in shooting down the coal and in loading it on pit cars.

With dust defined as coal that will pass through a 20-mesh sieve, these figures indicate that the amounts of dust made by the three cutting processes would be slightly less than 2.40, 1.06, and 1.11 per cent of the total coal to be produced by the undercuts.

Some tests [a] were made by the Fairmont Coal Company in one of their mines working the Pittsburg seam in the Fairmont district, West Virginia. The undercutting was done with electric punching machine and breast chain machine. One working face in which the coal was soft was cut by each machine, and in another part of the mine where the coal was harder similar cuts were made. The

[a] Described by C. E. Scott in Mines and Minerals, May, 1908, p. 477.

depth of each cut was 4 feet. As it is the practice of this company to "block" or "snub" down the coal in the center of the room after cutting with a chain machine, this blocking was done in each instance to a height of 18 inches. The coal seam is indicated in a diagram in the published account as 8 feet thick.

The reported figures gave the weights of cuttings "over" and "through" various mesh from 1¼-inch to 80-mesh, and the percentage that each portion was of the total cuttings. In accordance with the definition of dust already given, only the cuttings that passed through 20-mesh will be considered here. In the following table the percentages of the different sizes have been refigured on a basis of the theoretical amount of coal produced from the undercut face, assuming a uniform thickness of seam of 8 feet and 82 pounds per cubic foot of coal in place.

Comparative weights of cuttings and percentages of total coal in Fairmont experiments.

	Chain (breast) machine.				Puncher.			
	"Soft" coal (cut 20 feet by 4 feet).		"Hard" coal (cut 16 feet by 4 feet).		"Soft" coal (cut 20 feet by 4 feet).		"Hard" coal (cut 16 feet by 4 feet).	
	Pounds.	Per cent.	Pounds.	Per cent.	Pounds.	Per cent.	Pounds.	Per cent.
Through 20-mesh....	439	0.84	431	1.03	558	1.06	641	1.53
Through 40-mesh....	211	.40	212	.50	274	.52	318	.76
Through 80-mesh....	126	.24	126	.30	165	.31	192	.46

Mr. George R. Wood, in a paper read before the Coal Mining Institute of America, June 29, 1909, made some comparisons of the dust produced by mining machines, as reported by Mr. Randolph, formerly with the Pittsburgh Coal Company. The results were given for dust passed through a 40-mesh sieve only, in pounds per square foot of undercutting, as follows:

Pounds of dust passed through 40-mesh sieve, per square foot of undercutting, by several methods.

Washington Coal and Coke Company mines, Connellsville region, Pennsylvania:	
Hand mining	1.80
Puncher machine	4.58
Chain machine with pick-point bits	1.48
Pittsburgh Coal Company, Midland No. 1:	
Puncher machine	6.18
Chain machine (two trials)	2.43 2.51

Comparison of the results of the foregoing series of machine-dust and hand-dust experiments can be made on the only size in common—40-mesh. In order to compare the weights of dust produced relative to the total amount mined, in compiling the following table the coal seam for each test was arbitrarily assumed to be 6 feet thick. The Fairmont percentages are refigured accordingly.

Comparative amounts of machine and hand cuttings passed through a 40-mesh sieve, in percentages of total coal produced, assuming a 6-foot seam.

	Chain machine.	Puncher.	Hand.
Westmoreland	0.49	1.25	0.41
Fairmont "soft" coal	.54	.70	
Fairmont "hard" coal	.67	1.01	
Washington Coal and Coke Company	[a] .30	.93	.37
Pittsburgh Coal Company, Midland No. 1	.49 .51	1.26	
Average	.50	1.03	.39

[a] Chain with pick points.

The figures for the chain machines are fairly close together, also the two tests of hand-pick undercutting, but the results of the puncher tests are too divergent, even after due allowance is made for the physical character of the coal and ability of puncher machine men.

Judging from the Fairmont figures the quantity of coal dust passing through a 20-mesh sieve is double what will pass through a 40-mesh sieve. If we assume the limit of dangerous coal dust as 20-mesh (the reason for this assumption will appear later), by doubling the above averages we get 1.00, 2.06, and 0.78 per cent of the total coal as dangerous dust. If we accept these figures for a mine producing 1,000 tons of coal per day, there would be from 15,000 to 41,000 pounds of dust produced daily from the undercutting, besides a certain additional amount from shooting down, picking, and shoveling the coarse coal. If only a small fraction of the coal dust daily produced in the ordinary mine is left exposed in rooms and along the entries, and not rendered inert by natural or artificial means, the mine will soon contain more than sufficient dust for propagating an explosion.

AGENCIES THAT DISTRIBUTE COAL DUST.

While coal dust mainly comes from breaking down coal at the face of the mine, it is distributed through the mine in several ways:

1. By the force of the explosive used.
2. By the shoveling of coal along the face and into pit cars.
3. By the fine coal running through cracks and holes in pit cars, and particularly under the car door, which usually fits more or less loosely, and thus being distributed along the haulage ways.

4. By lumps of coal jolting off the tops of pit cars and then being ground up by the traffic of men and mules or horses. This condition is found particularly at sidings and at the "main bottom," owing to abrupt stops while the cars are moved and switched.

5. By ventilating currents, which pick up the fine "float" dust at the face, and more particularly from the tops of cars. The passing of a trip of cars, partly blocking the air way, causes a very high velocity past the cars, especially when they go through a single ventilation door. If the hoisting shaft is dry and is a downcast, and the surface screens are near the top of the shaft, the ventilating currents may draw considerable quantities of dust from the screens.

Dry coal dust along the passageways or entries of a mine is a great menace. While in this country the great majority of dust explosions have originated at the face from blown-out or overcharged shots, the propagation has been through dusty entries. If the entries were free from dry coal dust the explosion would be local. Again, some explosions have originated on the entries from igniting pockets of gas in poorly ventilated entries; or in shooting down the roof for overcasts, or in brushing or grading. Firing shots on roadways has been a frequent source of disaster in England.

The problem is not alone to treat the dust lying on the floor, but the fine "float" dust that lodges on walls, roof, and timbers. Every ledge and projection has a coating of more or less thickness of the purest coal dust. In the opinion of many writers, what Mr. W. N. Atkinson terms "upper" dust is more dangerous than the "lower" dust, because it is more finely divided. This will evidently depend on the characteristics of the dust—whether it is coal dust or rock dust and whether the former retains its strength.

The ventilating currents have a sorting action, dropping the coarser particles to the floor and lodging the finer higher up.

EXPERIMENTS WITH EXPLOSIBLE COAL DUSTS.

EFFECT OF QUANTITY OR DENSITY OF DUST.

CHARACTER OF DUST USED.

A preliminary series of experiments have recently been made in the explosion gallery at the Pittsburg station to observe the effect of sizing fine coal, and to determine the quantity or density of the finest size necessary to propagate an explosion.

All these tests were made with artificially prepared dust from a certain mine working the Pittsburg seam, which provides coal of uniform character and chemical composition for all standardizing tests at the station.

EXPLOSION FROM COAL DUST IN GAS AND DUST GALLERY NO. 1, PITTSBURG TESTING STATION.

The coal as prepared after grinding and screening has the following average proximate analysis:

Proximate analysis of coal used for tests at Pittsburg station.

Moisture	1.94
Volatile combustible	35.11
Fixed carbon	57.73
Ash	5.22
	100.00
Sulphur	1.25

There is manifest advantage in using an artificially prepared dust of uniform chemical composition and known size. The use of so-called mine dust of unknown composition in the early experiments abroad, was probably the cause of inconsistency in many of the results reported.

The coal dust for the following density tests was made by grinding in a ball mill the standard Pittsburg station coal until it would all pass through a 200-mesh sieve (200 wires to the linear inch).

METHOD OF PROCEDURE.

In these tests, six sections (40 linear feet), of the explosion gallery were used. The gallery 100 feet long and 6 feet 4 inches in diameter, may be seen in Plate I, which shows the first stage of a dust explosion. The near end is closed by a concrete block, in which is placed the cannon for simulating blown-out shots. The gallery has 15 sections, each 6 feet 8 inches long, with a window on the observation side in the middle of each section and a relief door or flap at the middle of the top of each section. For the density tests the following arrangement was used: A paper diaphragm was placed at the farther end of the sixth section. The space between the diaphragm and the concrete block contained 1,260 cubic feet. Air was blown into the bottom of the gallery and drawn out at the top by two blowers with 5-inch inlets and outlets. These blowers, one for each three sections, were connected with the gallery by independent pipes. Each pipe formed with the gallery and its respective blower a separate circuit. The dust was placed in a short 6-inch pipe at the top of the gallery near the concrete block. A blast of compressed air ejected the dust from the pipe, which pointed toward the paper diaphragm and the farther end of the gallery.

The fans were started at the moment of dust ejection, to cause circulation of the air and so keep as much of the dust in suspension as possible. Nevertheless, it was found, by taking samples at the axis of the gallery, that the greater part of the dust fell quickly to the floor. In eighty-five seconds only about 9 per cent remained in suspension, and in two hundred and seventy-five seconds about 4 per cent. If followed out, the curve showing the rate of fall made by platting the several results makes it probable that after two hundred and ninety seconds, the average time before the shots were fired, there was not in suspension at the middle of the gallery over 2½ per cent of the original amount of dust injected.

METHOD OF TAKING SAMPLES.

The samples of the dust in suspension were gathered by a special device consisting of a small tube in which dried cotton served as a filter. This filter tube was attached to a long, thick glass tube, which was inserted into the gallery through a hole in a paper diaphragm placed over the third top relief valve of the gallery, 17 feet from the firing end, so that the filter tube could be placed to draw air and dust from the center or axial line of the gallery, and at a point where the end of the flame from the blown-out shot would impinge. Suction was produced by emptying water from a bottle of 4 liters capacity. The long glass tube was connected with the top of the bottle by a rubber hose. The water from the bottle was discharged downward through a rubber hose into a similar bottle below. The filter tube was dried and weighed before insertion and after gathering the sample was again dried and weighed, the difference in weight giving the amount of dust in suspension in 4 liters of the gallery atmosphere, at the average time of taking the sample. Check samples were taken simultaneously with duplicate apparatus. This apparatus, designed by Dr. J. C. W. Frazer, was found to work admirably. Some inconsistency in the amounts of dust in suspension was evidently due to the irregularity of the air currents and the method of injecting the dust, rather than to the method of sampling. Similar devices for obtaining the amount of dust in mine air are described by Prof. Otto Brunck, of the Royal Saxon Mining School, Freiberg;[a] and a more portable form, in which the filter tube is attached to a brass exhausting syringe of 200 cubic centimeters or more capacity, is described by Dr. J. S. Haldane in his valuable little book, "The investigation of mine air" (p. 57).

RESULTS.

Five tests of dust were made under the conditions named, with amounts varying from 2 to 5 pounds. The results are shown in the table below. As already stated the fans were started at once after the dust was injected into the gallery by the blast of compressed air. One minute later the first sampling of dust in suspension, in duplicate, was begun, and lasted approximately one minute. After an interval of another minute, a second sample was taken, also in duplicate. Then

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[a] Die chemische Untersuchung der Grupenwetter, p. 91.

the fans were cut out by valves, and the shot was fired about two minutes later. The time given in the tabulation of the results is the period from the moment of injecting the dust to the middle point of the time used to take the sample.

Ignition of the dust was considered to have occurred in all five tests, and complete propagation in all but test G–2891, in which the coal-dust charge was 2 pounds, equivalent to 0.0253 ounces per cubic foot (or 25.3 grams per cubic meter) for the 40 lineal feet of gallery used in the tests.

Results of explosion-gallery experiments on explosibility of 200-mesh dust (more or less in suspension).

No.	Gallery test No.	Date of test (1909).	Explosive used in shot.	Amount of dust used.			Flame showed (indicating its length) at—		Ignition.	Propagation.	Time from start of test to sample taking.	Dust density per cubic foot.[a]
				Pounds.	Ounces per cubic foot.	Grams per cubic meter.	Doorways Nos.—	Windows Nos.—				
											Seconds	*Ozs.*
1	G–2887..	Sept. 7..	No charge[b].....	5½	0.0698	69.8	......	......	......	......	85 210 325	.... 0.00195 .00123
2	G–2888..	...do.....	1¼ pounds (567 grams) FFF black powder.	5	.0635	63.5	1–7	1–9	Yes.	Yes.	97 285 390	.00208 .00063 .0007
3	G–2890..	Sept. 8..	.....do..........	3	.0381	38.1	1–5	1–6	Yes.	Yes.	85 275 282	.00375 .00168 .00175
4	G–2891..	...do.....	.....do..........	2	.0253	25.3	1–3	1–4	Yes.	No..	85 282 390	.00243 .00073 .0007
5	G–2892..	...do	.....do..........	2½	.0317	31.7	1–5	1–6	Yes.	Yes.	85 300 405	.00298 .00168 .0016
6	G–2896..	Sept. 9..	1¼ pounds (567 grams) FFFF black powder.	2½	.0317	31.7	1–4	1–6	Yes.	Yes.	85 275 85 275	c.00255 c.0009 .00275 .0010

[a] Grams per cubic meter can be obtained, approximately correct, from ounces per cubic foot by multiplying by 1,000.
[b] No charge of powder fired; this test was made to observe the density of dust at successive intervals following injection.
[c] All samples were taken at door 3 except these two in test 6, which were taken at door 1.

Analyses of 200-mesh dust used in experiments and of coked dust resulting from them.

Test No.	Character of sample.	Moisture.	Volatile combustible.	Fixed carbon.	Ash.
All.......	Average dust.....................................	2.00	34.00	59.70	4.30
G–2892...	Coked dust......................................	[a] 2.00	14.49	65.59	[b] 17.92
G–2896...	.....do...	[a] 2.02	13.78	67.42	16.78

[a] Analyses of these coked dusts were not made until over six weeks after the test; it is probable that the moisture shown had been absorbed in the meantime.
[b] In the explosion of the coal dust, the analysis of which is given in the first line of the table, the quantity of ash for a given amount of the dust would remain unchanged, as in this experiment there was no contamination. Hence it is possible to calculate the total amount of combustible matter disappearing in the explosion and the distribution of this combustible matter between the volatile matter and the fixed carbon. The following result is obtained: That 89.4 per cent of the volatile matter of the original dust and 73.6 per cent of its fixed carbon have been consumed.

Although the sampling showed that a very small fraction of the coal dust remained in suspension, the propagation of explosive wave was proportionate in each instance to the total amount injected into the gallery, indicating that a considerable part of the dust that had fallen to the floor before the shooting was thrown into suspension by the concussion of the shot and in time to assist in the propagation of the flame. Not all of the dust was burned and portions of it had not lost all of its original volatile combustible matter, but the greater part was more or less coked.

COKED DUSTS PRODUCED BY EXPLOSIONS.

The coked dust produced in these tests developed some interesting peculiarities, as shown in Plate II. There are three types of coked dust. The first consists of large globular pieces, with large interior air cells and thin glazed walls, from one-fourth to three-fourths inch in diameter. The pieces of coke shown in Plate II were photographed on paper divided into half-inch squares, so that the actual size may be scaled from these squares. This type of coke was evidently produced by the flame striking a mass of floating particles, the concussion and heat causing them to cohere and distill their gas, the expansion of which within the melted mass blew it into the globular forms shown at the upper part of Plate II. These had time to cool and harden before they fell to the bottom of the gallery.

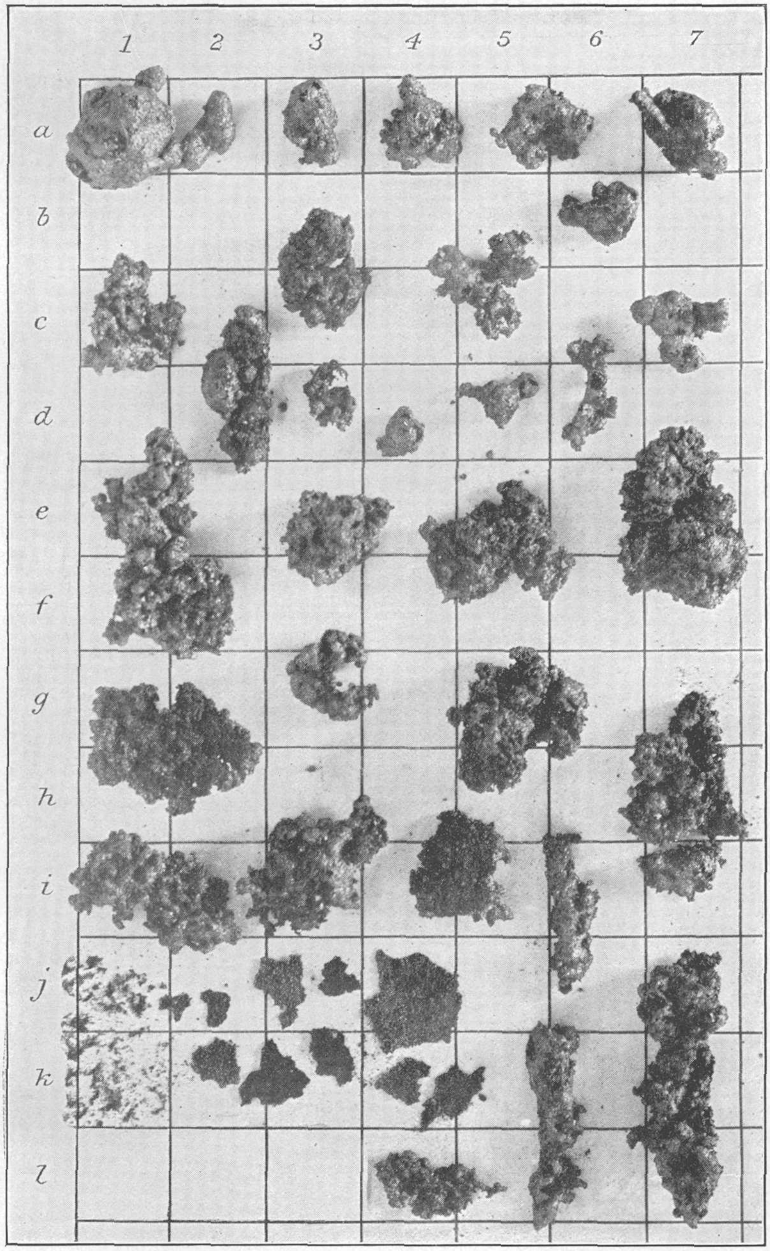
The second type of coke, shown in the middle portion of Plate II, consists of masses of loose particles, which have fallen while still hot, sticking to other masses and flattening on the floor of the gallery.

The third type, shown in the lower left corner of Plate II, is not a true coke but scales of particles evidently caked while lying on the floor of the gallery. The upper side of those on squares J–4, K–4, show minute bubbles of coke. The lower surface on square K–3 shows dust apparently little affected by the heat. These scales of caked dust are not thicker than one one-hundredth of an inch.

EFFECT OF DEGREE OF COARSENESS OF DUST.

RESULTS OF TESTS.

A series of tests was conducted in the explosion gallery of the Pittsburg station to determine how coarse a coal dust may be that, if abundantly present, will propagate an explosion that has been started by ignition from a blown-out shot. The results are shown in the two following tables:



COKED DUST FROM PITTSBURG GALLERY, DENSITY TEST WITH 200-MESH DUST.

Photographed natural size on paper divided into half-inch squares. Experiment G-2892.

Tests of propagation of flame by different sizes of coarse coal dust.

No.	Gallery test No.	Date of test (1909).	Explosive.		Dust used.[a]		Flame showed (indicating its length) at—		Result.	
			Pounds.	Grams.	Weight.	Size.	Doors Nos.—	Windows Nos.—	Ignition.	Propagation.
					Pounds.	*Mesh.*				
1	G-2882..	Sept. 3	1¼	567	10	20- 40	([b])	1- 4	No......	No.
2	G-2883..	Sept. 4	1¼	567	20	20- 40	([b])	1- 5	No......	No.
3	G-2884..	...do....	1¼	567	10	40- 60	0	1- 3	No......	No.
4	G-2885..	...do....	1¼	567	20	40- 60	0	1- 3	No......	No.
5	G-2886..	...do....	1¼	567	10	60- 80	2- 4	1- 5	Yes.....	No.
6	G-2889..	Sept. 7	1¼	567	20	60- 80	2- 6	1-14	Yes....	Yes.
7	G-2894..	Sept. 9	1¼	567	10	80-100	2- 7	1-14	Yes.....	Yes.
8	G-2895..	...do....	1¼	567	17	60- 80	2-14	1-14	Yes....	Yes.
9	G-2963..	Sept. 20	1¼	567	14	60- 80	3- 7	1-14	Yes.....	Yes.
10	G-2964..	...do....	2½	1,135	10	60- 80	3- 9	1-12	Yes.....	Yes.
11	G-2970..	Sept. 24	2½	1,135	10	60- 80	2-11	1-14	Yes....	Yes.
12	G-2974..	Sept. 25	2½	1,135	12	40- 60	2-12	1-14	Yes.....	Yes.
13	G-2987..	Sept. 27	2½	1,135	15	20- 40	2- 5	1- 8	Yes.....	Partial.
14	G-2988..	...do....	2½	1,135	23	20- 40	2- 3	1- 6	Yes.....	Partial.

[a] Dust was placed on a horse in the first three sections, and on shelves in sections 3-6, except in tests 13 and 14, in which dust was placed on shelves in sections 3-9 and 3-11, respectively.
[b] Edge of door 3.

Analyses of dust samples taken before and after tests shown in preceding table.

No.	Gallery test No.	Character of sample.	Moisture.	Volatile combustible.	Fixed carbon.	Ash.
1	G-2882..	Dust before shot	2.00	34.50	59.70	3.80
3	G-2884..	.....do	2.20	33.50	60.20	4.10
5	G-2886..	.....do	2.00	34.50	59.50	4.00
7	G-2894..	....do	2.00	35.00	58.60	4.40
		Coked dust after shot	[a]1.54	13.92	65.12	19.42
12	G-2974..	Dust before shot	2.20	33.50	60.20	4.10
		Coked dust after shot	2.60	12.00	68.70	16.70
13	G-2987..	Dust before shot	2.20	33.50	60.20	4.10
		Coked dust after shot	[a]1.28	18.18	69.62	10.92

[a] Analyses of these coked dusts were not made until over a month after the test; it is probable that the moisture shown had been absorbed in the meantime.

METHOD OF SCREENING.

The coal was of the kind used for standard tests at the station, the average analysis of which is shown on page 35. After being crushed and ground, it was passed through 20, 40, 60, and 80 mesh screens, so that four sizes of dust remained over 40, 60, 80, and 100 mesh screens. Difficulty was experienced in getting each size free from the next smaller size, and particularly from the float dust, so that great care was required in screening. The float dust was eliminated by stirring small portions of the screened size in a deep pail, with the end of a hose discharging compressed air. By this means each size when finally finished was remarkably clean and free from other sizes.

DISTRIBUTION OF DUST.

In this series of experiments, the dust of the size to be tried was distributed along the gallery on four narrow iron shelves on either side. The gross amount distributed was 1 pound per linear foot of gallery. This amount is much in excess of what is necessary to produce an explosion, so that only a relatively small part of the dust is active or loses its volatile matter. In addition to the dust placed as just described, 20 pounds was placed upon a horse 20 feet long and 9 inches below the center line of the bore hole and the axis of the gallery. The dust was placed in this way to obtain the most extreme condition, such as would be found in a mine with a blown-out shot

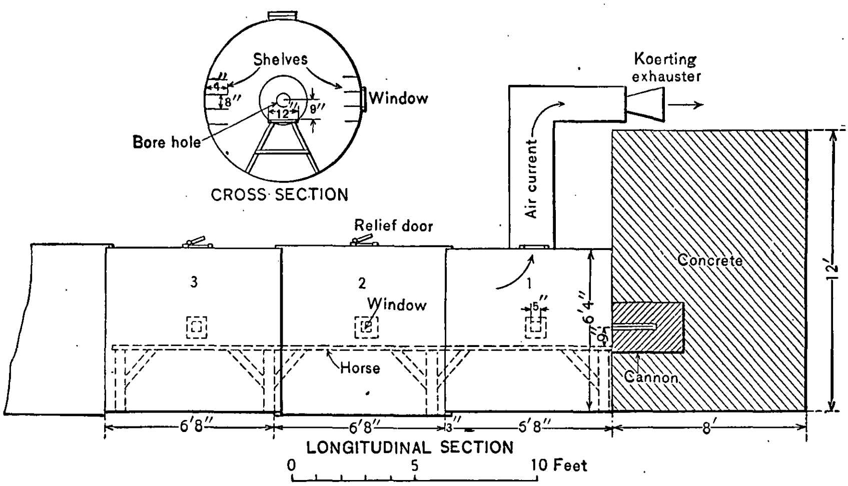


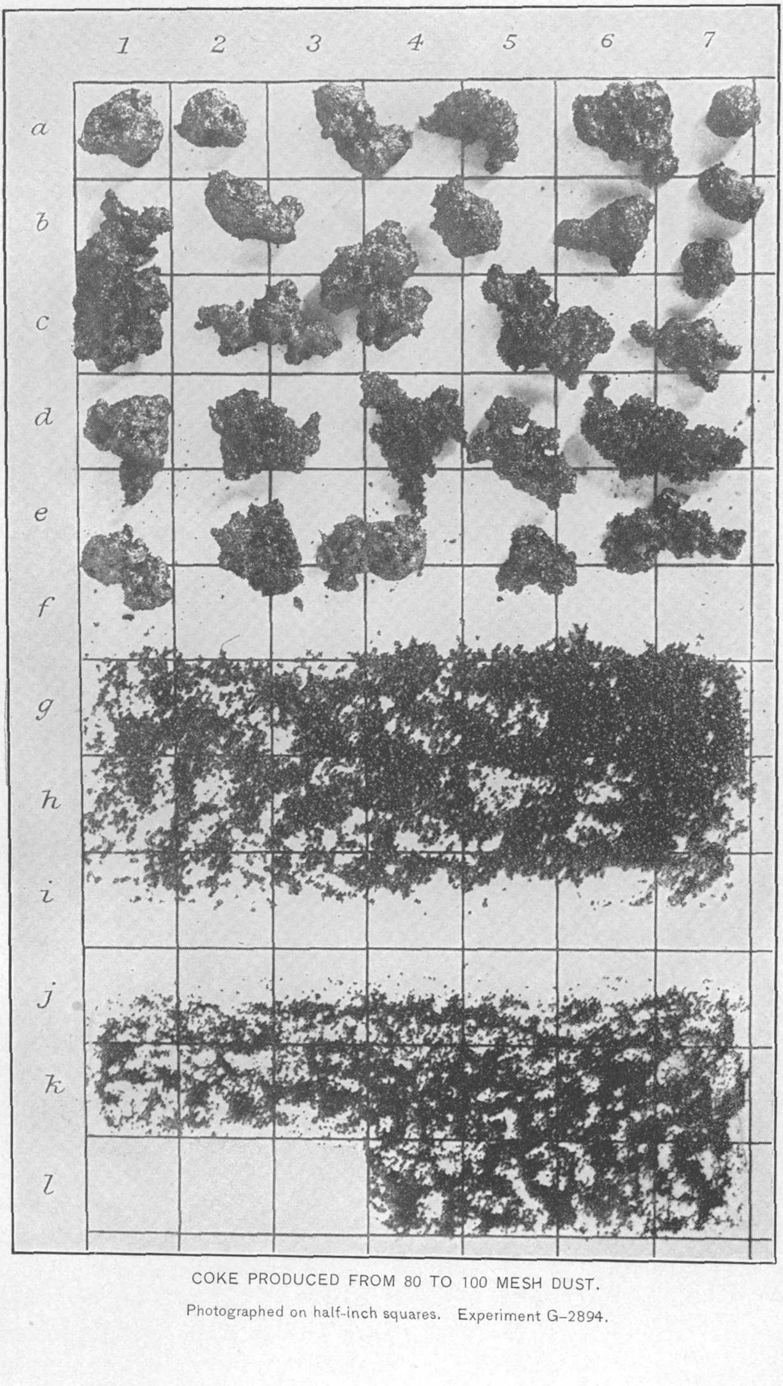
FIGURE 1.—Diagrammatic sections of cannon end of gallery No. 1, Pittsburg station.

pointed toward a pile of coal dust. Figure 1 is a sectional outline of part of the gallery, showing the location of the horse.

DISCUSSION OF RESULTS.

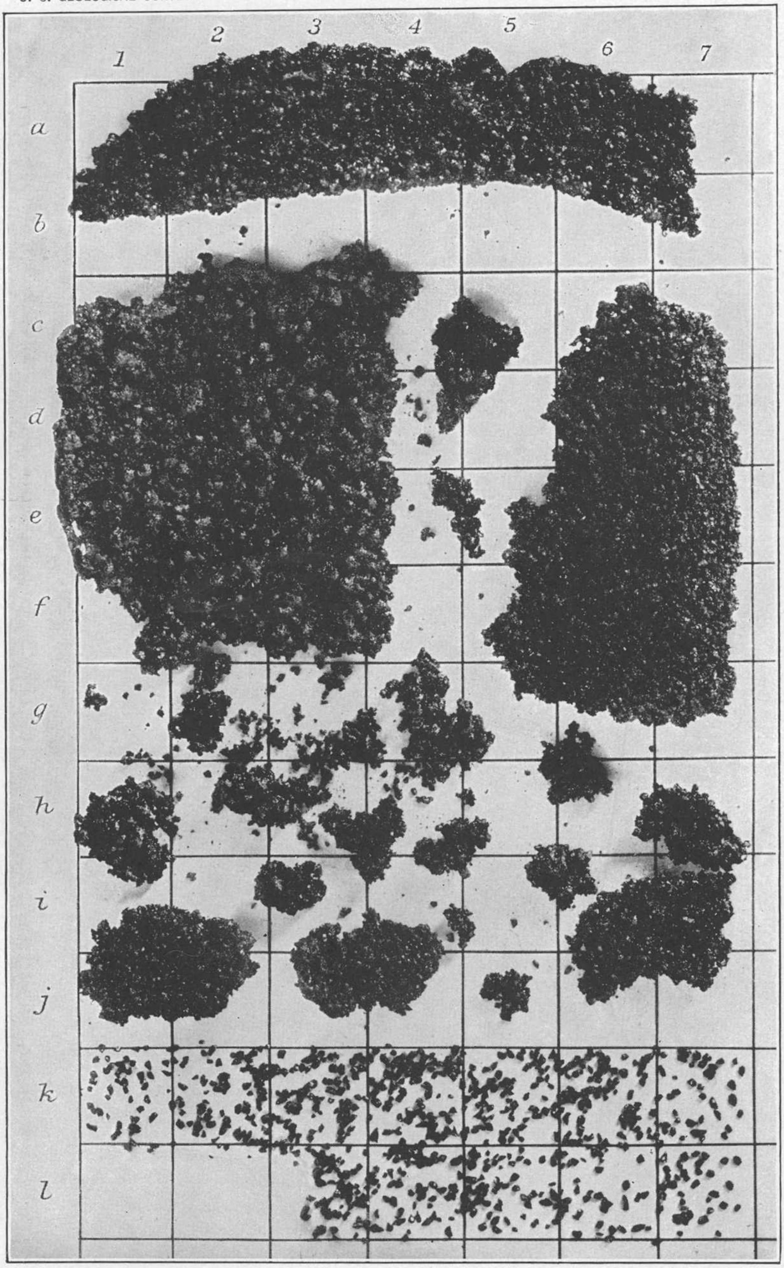
In the first tests a charge of 1¼ pounds of black powder was used, tamped with 2¼ pounds of clay. With this charge dusts larger than 60-mesh did not even ignite (except for slight prolongation of powder flame in tests 1 and 2), but 80 to 100 mesh dusts and also 60 to 80 mesh dusts in three out of four tests did ignite and propagate the explosion. It may be assumed that finer sizes would propagate, so no tests were made of them.

A series was then tried with double the quantity of black powder, or 2½ pounds, and with 2 pounds of clay tamping, which was all that the depth of the bore hole would allow. The effect was notable; 60 to 80 mesh dust propagated the explosion and so did 40 to 60 mesh dust. With 20 to 40 mesh dust, while there was ignition, there was only partial propagation, but the indications were that with a still larger



COKE PRODUCED FROM 80 TO 100 MESH DUST.

Photographed on half-inch squares. Experiment G-2894.



COKED DUST PRODUCED FROM 20 TO 40 MESH DUST.

Unused particles shown at the bottom. Photographed on half-inch squares. Experiment G-2987.

charge of powder, increasing the concussion and heat of the initial explosion, complete propagation would be produced. It may be that in a mine still coarser sizes would propagate from very large shots, in view of the fact that smaller sizes are present to sustain the flame; but tentatively, until further tests can be made, the writer has accepted 20-mesh as the dividing line between what may be termed fine coal and what may be considered dust.

It must not be inferred that larger particles of coal may not be a factor in a mine explosion once fairly started. On the contrary, the writer believes that they are, and that in a strong explosion the coal walls of the passageways where struck by a fierce blast will give up their quota of volatile gases. The assumption as to the size (20-mesh) therefore refers only to the *initial* stage of an explosion. Heretofore such coarse dust has not generally been considered dangerous.

CHARACTER OF COKE PRODUCED.

The coke produced in these tests presented some interesting peculiarities, as indicated in the photographs of coke from two typical explosions, reproduced in Plates III and IV. The first (Pl. III) from test G–2894, is the product of the explosion of "dust" finer than 80 and coarser than 100 mesh. The globular pieces shown in the upper part of the picture, which are from one-half to three-fourths inch in diameter, resemble the coke from float dust, though more irregular and made up of a mass of smaller cells. The smaller particles in the middle of the picture (obtained by screening) are largely spherical, and many consist of a single cell. The finest particles, at the bottom of the picture, are finer cells, also fragments of larger coke cells.

Plate IV shows coke and coal particles from test G–2987, in which a partial propagation was obtained from "dust" finer than 20 and coarser than 40 mesh. Particles of this "dust" which were not used in the experiment are shown in the lower part of the picture. The large crumbly masses of coke in the upper part of the picture consist of individual coked and caked particles loosely stuck together as they were swept into little piles at the flanges of the gallery.

The piece at the top which has the same thickness as width, three-fourths inch, was formed in the corner of a flange. The piece on the squares C–6 and 7 to G–6 and 7 shows the under side of such a mass with the coal particles caked or fused only enough to stick together.

EFFECT OF CHEMICAL COMPOSITION.

PAST EXPERIMENTS.

The effect of the chemical composition of dusts upon their relative explosibility or nonexplosibility is a problem that has been much discussed by mining men and by scientists from the time of Faraday. Experiments with dust of different chemical composition have been made at various times and in various countries, both in laboratories and on a larger scale. The earlier experiments of the foreign investigators, Abel, Hall, Galloway, Marreco, and others, and of the early European testing stations, have been mentioned on pages 12–19. The small-scale experiments of Professors Peckham and Peck, of the United States, have been referred to on page 23.

INVESTIGATIONS IN THE UNITED STATES BY CHAMBERLIN.

No large-scale systematic tests of the explosibility of coal dust had been made in this country before the Pittsburg station experiments were started; but some very interesting studies of explosive mine gases and dust have been made by Mr. Rollin Thomas Chamberlin.[a] The investigations relating to coal dust were made to determine the part that dust took in explosions, particularly in the Monongah, Naomi, and Darr disasters. Mr. Chamberlin observed the enormous quantity of fine coal dust coating everything in the exploded mines. He noted that the dust was of two sorts, "uncharred dust" and "charred dust," and that each took certain positions with reference to the obstructions in the passageways. He observed that the charred dust in the Monongah and Darr mines was for the most part on exposures facing away from the source of the explosion, but adds that there were many exceptions to the rule. He concluded that much dust was coked while in the air and deposited in a semiplastic condition. Laboratory experiments were made by Mr. Chamberlin on the loss of volatile matter in the charred dust. In these investigations he determined the amount of volatile matter contained in different coal dusts, and the amount of gas given up in the process of crushing coal to dust, and also made some investigations of the relative inflammability of old and new dust. From the latter studies he concluded that the oxygen absorbed by dust is mainly chemically combined and that there is not enough free oxygen in the dust to play an important part in an explosion. He therefore inferred that "fresh dust is likely to prove more inflammable and more predisposed to start and propagate a dust explosion."

EXPERIMENTS OF BEDSON AND WIDDAS.

Abroad, during the past few years, valuable tests of the comparative sensitiveness of different dusts have been made on a laboratory scale by Professors Bedson and Widdas at Newcastle University, England. Preliminary results were given by them in two papers read before the North of England Institute of Mining and Mechanical Engineers, 1906–7. These results are discussed by Dr. J. C. W. Frazer on pages 117–121 of this bulletin.

[a] Chamberlin, R. T., Notes on explosive mine gases and dusts, with special reference to explosions in the Monongah, Darr, and Naomi coal mines: Bull. U. S. Geol. Survey No. 383, 1909.

INVESTIGATION IN FRANCE BY TAFFANEL.

M. J. Taffanel, in August, 1907, published the results of his first year's experiments at the Liévin station. A large number of tests were made with the coals from the several mines of the Pas de Calais district. M. Taffanel, believing that a uniform density of dust cloud was necessary to obtain consistent results, arranged a closed-circuit gallery. (See fig. 12.) This consisted of two parallel sheet-iron pipes 2 feet in diameter. These pipes were 25 feet long and connected at the ends. In one of the pipes there was a disk fan for propelling the air current and mixing the dust. The four openings to the gallery were closed by paper diaphragms. The inclosed volume was 152 cubic feet. In operation, the fan was started and the dust put in gradually, and after time had been given for circulation four or five times around the closed circuit at a speed of 13.16 feet per second, a cannon charged with a half stick of dynamite, weighing 1.12 to 1.33 ounces (32 to 38 grams), and not tamped, was fired through one of the paper diaphragms.

The dusts were always passed through a French 200-mesh sieve, equivalent to English 190 mesh. The dust put into the gallery was weighed and it was assumed that all was put into suspension.

The most sensitive dust was found to be that from the Courrières mine. In one instance, with as low a weight of dust per cubic foot as 0.023 ounce or 23 grams per cubic meter the flame traversed the tube and came out about half a yard. However, this was the only instance in which a flame was produced, out of three experiments tried with that density of dust. With this exception, it was only when as much as double this density, or 0.046 ounce, was used that flame was occasionally produced. With 0.070 ounce per cubic foot, or 70 grams per cubic meter, explosions were produced quite regularly with almost all the coals except anthracite. With this, as high a dust weight as 0.222 ounce per cubic foot (222 grams per cubic meter) were tried without producing continued flame.

Taffanel's conclusions were as follows:[a]

The experiments show, in the first place, that for most of the dusts tested it does not require large quantities of fine dust, once put in suspension, to form an inflammable cloud. A mine road where 0.1 ounce of fine dust per cubic foot [100 grams per cubic meter] may be collected is generally regarded as [but a] little dusty. It is important to observe that so far the experiments have been confined to screen dusts, which are purer and without doubt more inflammable than those from the mine.

We see, in the second place, that the small charge represented by half a cartridge of gelatin dynamite is above the "charge limit" for most of the dusts tried. This, of course, refers to the "charge limit" without stemming.

Finally, we remark that for the eight types of dust tested the increasing order of inflammability is the same as the increasing percentage of volatile matter. Strictly

[a] Premier essais sur l'inflammabilité des poussières, p. 20; Proc. South Wales Inst. Eng., vol. 26, No. 3, 1909, p. 677.

speaking, it may be considered that the dusts differentiate not only by their percentage of volatile matter, but also by other elements of their composition, particularly by the percentage of ash. But the dusts tested, coming nearly all from the screens, have a somewhat similar percentage of ash, which causes the factor "volatile matter" to predominate. The ash intervenes in two ways: First, by its weight; the cloud densities indicated in the above tables are gross densities; it would be more just to compare the densities by reckoning only the combustible portion, after deduction of the ash and moisture; in the second place, the ash intervenes as an inert matter absorbing a part of the heat of combustion of the dust; it would be too hazardous to try to calculate this latter influence, which might without doubt be determined by experiment. But in the following table account is taken of the first influence by showing, alongside the gross densities, the densities calculated by deducting the ash and the moisture. This table places clearly in evidence the influence of the percentage of volatile matter.

Coal.	Percentage of volatile matter (ash and moisture deducted).	Cloud densities from which inflammations commence.		Cloud densities from which inflammations always occur.	
		Gross.	Calculated (ash and moisture deducted).	Gross.	Calculated (ash and moisture deducted).
		Oz. per cu. ft.	Oz. per cu. ft.	Oz. per cu. ft.	Oz. per cu. ft.
Anthracite[a]	11.2				
Lens 2 [a]	11.3	....	....	....	....
Dourges	15.4	0.138	0.120	0.138	0.120
Lens 1	26.6	.070	.060	.104	.090
Lievin 1-3	28.4-31.4	.046	.039-.044	.07-.074	.067-.068
Bruay	30.0	.038	.033	.092	.080
Courrières	30.6	.023	.021	.058	.052
Lignite	53.3	.030	.023	.040	.031

[a] No inflammation.

By the aid of these numerical results, which, it must not be forgotten, are approximate, may be drawn the conclusion that there are great differences in inflammability, under the conditions of the experiments, between the three following groups: First, anthracite and Lens 2, not ignited; second, Dourges and Lens 1, inflammable, but without great effects of flame, and with a marked tendency to stifling; lastly, the four types richest in volatile matter, which were ignited at low densities and which produced increased flames as the cloud density increased.

COMPARISON OF TAFFANEL'S METHODS WITH THOSE USED AT PITTSBURG GALLERY.

The few density tests made at the Pittsburg station (described on pp. 34–38) were all made with the high-volatile coal from the Pittsburg seam. While they were not numerous enough for a direct comparison with M. Taffanel's results, as given above, it would appear that the initiating charge of explosive was a most important factor.

M. Taffanel, in the experiments described above, used but 1.12 to 1.33 ounces of a low-grade nitro-explosive, while in the Pittsburg density tests, in a much larger gallery, 1¼ pounds of black powder was used. With this charge dust explosions were produced with as low a density of coal dust as 0.032 ounce of dust per cubic foot of space in the gallery (32 grams per cubic meter), as reported in the table on page 37.

M. Taffanel has recently written a paper on his tests in the larger gallery at Liévin.[a] These tests confirm those made previously in a smaller gallery. He has devoted much attention to the chemistry of dust explosions. He finds that schist (shale) dust tends to blanket the effects of the coal-dust explosions, but he states that his experiments in this direction have not gone far enough to permit conclusions to be drawn therefrom. His aim, in this first series of experiments, unlike that of the Altofts station, which will be mentioned hereafter (p. 80), had been to find the effect of mixing this schist dust with the coal.

INFORMAL TESTS AT PITTSBURG STATION.

There has not yet been opportunity at the Pittsburg station for systematically testing in the gallery the relative explosibility of dusts of different chemical composition; but Clarence Hall, in charge of explosives testing at the station, has made a great many informal tests of coal dust from different parts of the United States, and has kept careful records of them. These records he has kindly put at the writer's disposal. Certain tests have been selected as typical, and these are given in a table below. The materials range from anthracite with little volatile matter to subbituminous coal with much moisture and volatile matter. All shots were made with black powder, except one with dynamite. The weight of the charge is specified in the table. Clay tamping was used in all these tests. The amount of coal dust was usually 120 pounds, of which 20 pounds was placed on a horse and 100 pounds distributed on side shelves running along the full length of the gallery, 1 pound per linear foot. When the full number of shelves was not used, the loading was proportionately less. The horse or center shelf is placed in front of and 9 inches below the center line of the bore hole, so that the flame of the explosive would touch but not directly play upon the dust. This arrangement simulates the condition in a mine where a pile of coal with dust on it lies in front of a blow-out shot.

The charge of coal dust averages 1.2 pounds per linear foot of the gallery, equal to 0.61 ounce per cubic foot, or 610 grams per cubic meter. According to Taffanel, the theoretical weight of coal dust necessary to produce a maximum explosion is about 0.111 ounce per cubic foot or 111 grams per cubic meter.[b] Naturally this weight

[a] Les résultats obtenus jusqu'à ce jour dans la galerie d'essais de Liévin: Bulletin et comptes rendus mensuels de la Société de l'industrie minérale, February, 1909.

[b] This is figuring that "the total combustion of the carbon and volatile matter, with the exclusive formation of carbonic acid and water vapor, would exactly absorb all the oxygen of the air" (loc. cit.). In reality only a portion of the volatile matter and fixed carbon is burned. See analyses of coked dusts in reports of experiments, also footnote b to second table on p. 37.

varies somewhat with the character of coal.[a] The gallery at Pittsburg is charged with dust much in excess of the theoretical amount to insure the most severe conditions in testing explosives, but repeated tests have shown that dust through a 100-mesh sieve can be put in suspension by the concussion of 1¼ pounds of black powder if the dust is merely placed on the floor of the gallery. For the tests given in the table, the coal was ground until it would pass through a 100-mesh screen, but when road dust was tested it was used in the gallery as received.

No propagated explosion has been obtained with anthracite dust, although several tests have been made with a low-volatile anthracite (under 5 per cent volatile combustible matter) and with a higher volatile anthracite (8.32 per cent volatile combustible matter). However, it must not be concluded that these tests are final; there may be conditions under which propagation can be obtained.

Propagation did not take place with one semibituminous dust when dynamite was used for the firing charge, nor in one test when black powder size CC was used, but in subsequent tests, with other sizes of black powder, complete propagation followed. The failures to propagate may have been accidental, but considered together with the slowness of propagation observed in the other tests on this coal they indicate that it is not so sensitive as most bituminous coals.

With other semibituminous coals and all bituminous and subbituminous coals propagation of flame and explosion was complete. As these dust tests could only be made occasionally, when the gallery was not occupied by the more pressing testing of short-flame or so-called safety explosives, quantitative results on the relative sensitiveness of different bituminous dusts could not be attempted under the circumstances. But these typical tests and numerous other informal tests of the same character have demonstrated effectively the explosibility of coal dust.

The explosion propagative results with bituminous dusts have been so uniform that it is hard to understand the difficulty which early foreign experimenters had in obtaining consistent results, unless it was due to the uncertain character of the mine dust, or possibly to the very small charges of explosive employed.

[a] The theoretical quantity of the standard coal used for tests in the Pittsburg station, required for the complete exhaustion of the oxygen of a cubic foot of air by combination with all the combustible matter of the coal, was 0.123 ounce or 123 grams per cubic meter. This is based on the ultimate analysis of a sample (10556F) which was mined December 7, 1909, and analyzed June 27, 1910. The exposure for six months probably increased the oxygen contents and decreased the efficiency of the coal. The ultimate and proximate analyses of this coal are as follows:

Ultimate analysis.		*Proximate analysis.*	
Hydrogen	5.61	Moisture	2.59
Carbon	78.00	Volatile matter	35.34
Nitrogen	1.52	Fixed carbon	57.46
Oxygen	9.74	Ash	4.61
Sulphur	.52		100.00
Ash	4.61		
	100.00		

Explosion-gallery tests at Pittsburg station on dusts from representative coals.

Test No.	Date of test (1909).	Explosive used.	Dust on horse and shelves in sections Nos.—	Flame showed (indicating its length) at— Doors Nos.—	Flame showed (indicating its length) at— Windows Nos.—	Length of flame beyond dust zone.	Ignition.	Propagation.
						Feet.		
G-700..	Jan. 30..	500 grams FFF black powder.	1-15	1-6	1-6	0	Slight.	No.
G-3043.	Oct. 9...	.....do....................	1-15	(a)	1-3	0	No....	No.[b]
G-2369.	May 15..	500 grams C black powder.	1-15	1-3, 11-12	1-15	(a)	Yes...	Yes.[c]
G-2365.	...do.....	300 grams dynamite.......	1-15	....	....	0	No....	No.[d]
G-2067.	Apr. 10..	375 grams FF black powder.	4-9	1-15	1-15	[e]50	Yes...	Yes.
G-467..	Jan. 2...	500 grams FFF black powder.	4-5	1-9	....	27	Yes...	Yes.
G-465..	...do.....	.....do....................	4-6	1-12	1-15	60	Yes...	Yes.
G-2116.	Apr. 17..	375 grams FF black powder.	1-15	1-15	1-15	(a)	Yes...	Yes.
G-2156.	Apr. 24..	.....do....................	1-15	1-15	1-15	[e]50	Yes...	Yes.
G-2517.	June 19..	375 grams FF potassium nitrate powder.	1-15	1-15	1-15	(a)	Yes...	Yes.
G-1501.	Mar. 20..	375 grams FFF black powder.	1-15	1-15	1-15	(a)	Yes...	Yes.
G-2112.	Apr. 17..	375 grams FF black powder.	4-6	1-15	1-15	60	Yes...	Yes.

Test No.	Source of coal dust. Name of mine.	Source of coal dust. Location of mine.	Source of coal dust. Character and place of sample.	Analyses. Moisture.	Analyses. Volatile combustible.	Analyses. Fixed carbon.	Analyses. Ash.	Analyses. Sulphur.
G-700..	No. 2 Bear Valley shaft.	Williamstown, Pa.	Anthracite from first heading in the Little View at No. 2 shaft.	2.36	4.22	83.44	9.98	0.49
G-3043.	Connell Anthracite Mining Co.	Bernice, Pa...	Subanthracite from interior of mine.	1.40	8.32	75.52	14.76	......
G-2369.	No. 37 B mine...	Windber, Pa..	Semibituminous........	.77	13.96	79.80	5.47	.87
G-2365.	.....do..........	.....do.......	.....do..................	.77	13.96	79.80	5.47	.87
G-2067.	Shamokin mine.	Switchback, W. Va.	Semibituminous from tipple.	.84	15.16	79.90	4.10	.48
G-467..	Mine No. 5, Whitwell mines.	Whitwell, Tenn.	Bituminous from dry coal elevator.[f]	13.18	19.97	56.37	10.48	.77
			Bituminous from main entry.[g]	3.41	17.98	47.22	31.39	1.20
G-465..	No. 3 Tenn. C. and I. Co.	Blocton, Ala..	Bituminous from tipple.[f]	2.07	26.69	58.01	18.23	.82
	No. 7 Tenn. C. and I. Co.		Bituminous from ribs and timbers.[g]	3.22	24.18	49.34	23.26	.71
G-2116.	Federal Shaft mine.	Fairmont, W. Va.	Bituminous from interior.[f]	1.52	30.59	56.79	11.10	2.00
			Bituminous from tipple.[g]	1.25	31.70	57.34	9.71	2.41
G-2156.	Sunday Creek Co., No. 114.	Longacre, W. Va.	Bituminous from No. 2 Kanawha gas seam.	1.64	31.54	64.55	2.27	.69
G-2517.	Oak mine.......	Oak Station, Pa.	Bituminous ("standard" dust).	1.81	33.52	59.36	5.31	1.00
G-1501.	Garside mine....	Salineville, Ohio.	Bituminous...........	2.03	35.37	57.00	5.60	2.38
G-2112.	Superior Coal Co. No. C.	Sweetwater, Wyo.	Subbituminous from face of room 1 off first north.	9.63	34.49	50.91	4.97	1.05

[a] Not recorded.
[b] This test was repeated with 40 per cent dynamite with same result.
[c] This test was repeated twice with black powder, sizes "CC" and "CCC." "CC" did not result in an ignition, but "CCC" did.
[d] This test was repeated with a similar result.
[e] Flame extended 50 feet beyond end of gallery.
[f] Dust placed on a horse in the tests.
[g] Dust placed on shelves in the tests.

INFORMAL TESTS WITH ROAD DUST.

Some informal tests were made at intervals during the past year at the request of various mining men. The results of a few of special interest are given in the table below. The last three were with road dusts, which had a large admixture of clay or shale. The total ash ranged from 30 to 57 per cent. In two tests there was complete propagation, but in one test, in which the combined material had a total of 53 per cent ash, the flame died away, reaching only half the length of the gallery.

With regard to road dust, it is important to bear in mind that unless the shale or stone dust is very fine and is intimately mixed with the coal dust its presence has very little deterrent influence on the explosion. A concussion from a blown-out shot or a small explosion of fire damp does not throw the pieces of rock into the air if they are coarse, and therefore the dust cloud may consist only of the fine, pure coal dust that rises from around the rock fragments. The same is true of any large pieces of coal that are present. The question in regard to any road dust is whether there is sufficient fine coal dust among the coarser pieces of rock to rise and form a dust cloud of sufficient density to permit a propagation of flame.

Special explosion-gallery tests with bone dust, road dust, and mixtures.

Test No.	Date of test.	Black powder used.		Dust on horse and shelves in sections Nos.—	Flame showed (indicating its length) at—		Length of flame beyond dust zone.	Ignition.	Propagation.
		Size.	Weight.		Doors Nos.—	Windows Nos.—			
			Grams.				Feet.		
G-693	Jan. 29, 1909	F	500	0	1- 6	1-11	54	Yes	Yes.
G-415	Dec. 30, 1908	FFF	500	4- 6	1-15	1-15	60	Yes	Yes.
G-491	Jan. 9, 1909	FFF	500	4- 6	1-15	1-15	60	Yes	Yes.
G-1431	Mar. 13, 1909	FFF	375	1-15	1- 8	1- 8	0	Yes	No.
G-398	Dec. 26, 1908	FFF	500	[a] 4- 6	2	1- 9	20	Yes	Yes.
G-2962	Sept. 18, 1909	([b])	375	1-12	1-15	1-15	[c] 60	Yes	Yes.

Test No.	Source of coal dust.			Analyses.				
	Name of mine.	Location of mine.	Character and source of sample.	Moisture.	Volatile combustible.	Fixed carbon.	Ash.	Sulphur.
G-693	Bear Creek No. 3	Bear Creek, Mont.	Subbituminous coal and bone cuttings.	8.94	30.57	43.49	17.00	1.78
G-415	Weaver mine	Gallup, N. Mex	Subbituminous, taken from roads.	9.13	31.87	41.42	17.58	.59
G-491	Penn Gas Coal Co. No. 3.	Irwin, Pa	Bituminous, taken from roads.	2.50	26.06	53.43	18.01	1.24
G-1431	Elkins C. and C. Co.	Elkins, W. Va.	Bituminous, taken from roadway.	1.02	12.76	32.94	53.28	2.14
G-398	Carbon mine	Carbon, W. Va.	Coal dust and fire clay from room 12.	2.75	15.45	24.85	56.95	1.48
G-2962	Bunson Coal Co	Georgetown, Ill	Bituminous coal dust, 50 per cent.	10.66	29.44	45.00	14.90	2.29
			Clay, soapstone, and coal, 50 per cent.	6.41	19.45	27.18	46.96	1.49

[a] Dust placed on floor in sections 1-3 and not on horse.
[b] Size not given.
[c] Flame extended 40 feet beyond end of gallery.

EXPERIMENTS AT PITTSBURG WITH COAL DUST.

USE OF COAL DUST FOR TAMPING.

In various parts of the country the practice of using machine cuttings ("bug dust") or other coal dust for tamping has become very common. Some mining men have had a theory that if coal-dust tamping was dampened or made wet it would be rendered harmless. With a view to determining this point, a number of experiments were made in gallery 1 at the Pittsburg station with black powder, using machine cuttings, dry and wet, for tamping. The wet dust was wet enough to pack in the hand, and in the tamping a little water was squeezed out. The powder was protected from the damp dust by a paper wad. A statement of the results is given in the following table:

Explosion-gallery tests with machine cuttings ("bug dust") used for tamping.[a]

Test No.	Date of test (1909).	Powder.		Tamping.		Flame showed at—		Length of flame.[b]
		Size.	Weight.	Condition.	Weight.	Doors Nos.—	Windows Nos.—	
			Grams.		*Grams.*			*Feet.*
G-2909.	Sept. 11	FFF..	1,134	(c)	(c)	1-2	1-3	18
G-3046.	Oct. 14	FFF..	1,134	Wet........................	400	(d)	1-5	30
G-3047.	Oct. 14	FFF..	1,134	Dry........................	400	(d)	1-3	18
G-3086.	Oct. 23	FFF..	567	Wet........................	1,200	1-3	1-4	24
G-3085.	Oct. 23	FFF..	567	Dry........................	1,200	1-5	1-7	44
G-3082.	Oct. 21	FFF..	1,134	Wet........................	1,200	1-5	1-8	50
G-3083.	Oct. 21	FFF..	1,134	Dry........................	1,200	1-7	1-10	64

[a] The dust used for tamping was bituminous coal from the Keystone mine, McDowell County, W. Va., with the following analysis: Moisture, 1.24 per cent; volatile matter, 14.03; fixed carbon, 73.53; ash, 11.20; sulphur, 0.66. In all the tests with tamping the walls of the gallery were kept wet.
[b] Length of flame measured from the mouth of the blown-out shot to the last window showing. In each test the flame may have extended 6 feet farther, to a point just short of next successive window.
[c] No tamping used. The test was repeated with 567 and 1,701 grams of powder and the flame showed in the same number of windows. When clay was used, flame was seen in two windows, and occasionally in three.
[d] Not recorded.

The first experiments were made with 2½ pounds of black powder (1,134 grams) and 0.9 pound (400 grams) of machine cuttings. The effect with wet coal tamping was nearly to double the length of the flame from black powder alone, but with the dry tamping for some unexplained reason the flame was not materially lengthened in this test.

Experiments were then made with 1¼ pounds of black powder (567 grams) and 2.6 pounds (1,200 grams) of cuttings, wet and dry. With a smaller amount of powder than in the previous tests, the length of flame with the wet tamping was not quite so long as with the larger charge of powder but smaller amount of dust tamping. With the dry coal-dust tamping, the flame was two and one-half times as long as that of black powder alone.

A third set of experiments was tried with the same weight of coal tamping, but with 2½ pounds of black powder. The flame with the wet tamping was still more increased, being over 50 feet in total length, and with the dry tamping the flame was over 70 feet in length, causing, in fact, a limited explosion.

The length of flame from black powder without tamping does not appear to increase with size of charge as far as tested (2½ pounds), but it appears from these tests that the flame from the coal tamping increases with the charge of powder used. In fact, it is possible that a blown-out shot with a very large charge of black powder, such as is sometimes used in shots in mines of the interior coal province, that contains 8 pounds or more, and with coal dust for tamping, may cause a local dust explosion without the presence of any external dust. This may happen even in a wet entry. The tests with coal tamping at Pittsburg were made during rainy weather and with the gallery wet throughout by hose.

When very small charges of black powder are used wetting coal-dust tamping may make the length of flame slightly less than that with dry coal tamping, though the flame length would still be greater than that resulting with clay tamping; but when medium-size charges of black powder are used the heat is such that the water has little or no effect.

It is a reasonable conjecture, in view of the results of the experiments described above, that with larger charges of black powder moistening or wetting the coal-dust tamping would cause no appreciable decrease in the flame.

The conclusion is drawn from these experiments that the use of coal dust or coal cuttings for tamping, whether wet or dry, is a most dangerous practice. With a blown-out shot in which coal dust has been used for tamping, causing flame extending 50 to 70 feet or more if there is any dust along the room or entry, the chances of an extended dust explosion are enormously increased.

EXPERIMENTS WITH COAL DUST IN HUMIDIFIED AIR.

During the winter of 1908–9 experiments were made under the direction of Clarence Hall in explosion gallery 1 with standard 100-mesh dust distributed on horse and shelves and a current of humidified air drawn through the gallery. A Koerting injector used as an exhauster drew the air from a relief doorway near the "face" of the gallery. The intake air entering a relief doorway next to the outer end of the gallery was warmed by steam coils and humidified by compressed air and water sprays. The latter were of a type much used in cotton mills, in which the water is mixed with compressed air to finely pulverize the water spray. The gallery end was closed by a paper and cloth brattice and the intake air from the heating and humidifying box was drawn into the gallery through the last relief doorway and a box conduit by the Koeting injector. The results of the experiments are given in the following table:

Explosion-gallery tests to show effect of humidity.

[In all tests the explosive used was 1¼ pounds (567 grams) of black powder.]

Gallery test No.	Date of test.	Duration of test.	Air current.					Number of humidifier heads.[a]	Percentage of moisture in dust on shelves before shooting.	Flame showed (indicating its length) at—		Result.	
			Velocity (feet per minute).	Temperature.		Relative humidity.							
				Inside.	Outside.	Inside.	Outside.			Doors Nos. —	Windows Nos. —	Ignition.	Propagation.
		Hrs. min.		°F.	°F.								
G-346	Dec. 19, 1908	28	131	34½	34½	67	67	0	....	1-14	1-14	Yes.	Yes.
G-348	Dec. 20, 1908	1 46	104	61	39	89	60	10	1.91	1-14	1-14	Yes.	Yes.
G-349	Dec. 20, 1908	16 35	120	58	35	98.6	73	9	18.4	1-11	1-7	Yes.	No.
G-350	Dec. 21, 1908	24 18	123	59	34	82	65	6	11.63	1-7	1-11	Yes.	No.
G-482	Jan. 4, 1909	48 0	112	52	33	92.9	77	3	12.71	4-5	1-5	Yes.	No.
G-483	Jan. 7, 1909	48 0	96	53	21	95	75	6	26.19	2	1-4	Yes.	No.
G-484	Jan. 9, 1909	(b)	......	51	....	61	....	0	1.78	2-14	1-14	Yes.	Yes.
G-580	Jan. 19, 1909	70 0	132	44	30	90	81	2	2.15	1-14	1-14	Yes.	Yes.

[a] The humidifier heads of the small type used in cotton mills discharged water mixed with compressed air.
[b] A few minutes.

The first experiment (G–346) was made without humidifying, to observe the effect of an explosion of dust in the face of a current of air traveling 131 linear feet per minute. The explosion was propagated through the gallery.

In the second experiment (G–348) the relative humidity of the air was raised to 89 per cent, and the current was maintained for one hour and forty-six minutes. Practically no moisture had been deposited by this time, as indicated by the analysis of the coal dust, a sample of which was gathered from all shelves in the gallery. Complete ignition followed the shot.

In the third experiment (G–349) the average relative humidity was 98.6 per cent, and the current was kept on for sixteen hours and thirty-five minutes. A considerable amount of moisture was precipitated on the dust, the analysis showing the total moisture to be 18.4 per cent, or about 16.5 per cent in excess of the normal content of the coal dust. The result of the shot was a partial propagation, the flame dying down before it reached the end of the gallery.

In the fourth experiment (G–350) the relative humidity was 82 per cent and the total moisture of the dust on the shelves 11.63 per cent. There was also partial flame propagation in this test.

In the fifth experiment (G–482) the relative humidity was somewhat higher, but the percentage of moisture precipitated very little greater. The flame propagation, however, was much less, owing to some cause not apparent.

In the sixth experiment (G-483) the relative humidity of the air was still higher, 95 per cent, and the duration of the test the same, forty-eight hours. More moisture was precipitated than in the previous experiments, the average sample of dust on the shelves showing 26 per cent. In this experiment there was practically no propagation, only a slight ignition.

In the last experiment of this group (G-580) the experiment was made of not raising the temperature of the intake air. This averaged only 44° F. The relative humidity was maintained at 90 per cent, and the duration of the test was seventy hours, but owing to the low temperature practically no moisture was deposited on the coal dust and complete propagation ensued, as would be expected.

Another group of experiments was made under the direction of the writer during September, 1909. In these it was decided to mix a definite quantity of moisture with the coal dust and to humidify the air as far as possible with the limited volume of the sprays. Owing to insufficient number of sprays, the humidity could not be brought up to the point of depositing moisture upon the coal dust; therefore the propagation or nonpropagation of the explosion depended on the quantity of water mixed with the coal dust. The other conditions were the same as in the previous series of tests, except that the igniting charge was 2½ pounds of black powder instead of 1¼ pounds. The mixing was carefully done and occupied considerable time, as it is difficult to mix water directly with dust. After a stirring and kneading by hand, the wet dust was forced through screens to insure an even mixture. When the wet dust had been placed upon the shelves of the gallery, a sample was gathered from the dust at regular intervals through the gallery, and analyzed. The results of these experiments are given in the following tables:

Explosion-gallery tests to determine effect of humidity upon explosibility of coal dusts.

Gallery test No.	Date of test (1909).	Relative humidity.		Average velocity of air current.	Per cent of moisture in coal.	Flame showed (indicating its length) at—		Result.	
		Outside air.	Inside air.	Feet per minute.		Doors Nos.—	Windows Nos.—	Ignition.	Propagation.
G-2966	Sept. 21	....	78	85	8.00	2-14	1-15	Yes.......	Yes.
G-2967	Sept. 22	79	90	78	19.20	2-14	1-15	Yes.......	Yes.
G-2968	...do....	56	82	73	19.20	2-7	[b] 1-9	Yes.......	Yes.
G-2969	Sept. 23	77	90	89	29.70	2-6	[c] 1-4	Yes.......	No.
G-2971	Sept. 24	46	71	78	30.90	2-3	[d] 1-6	Yes.......	No.
G-2972	Sept. 25	53	83	74	11.80	2-14	1-15	Yes.......	Yes.
G-2973	...do....	54	80	86	30.70	2-3	1-3	Yes.......	No.

[a] In all tests, 20 pounds of 100-mesh or finer dust was placed on the horse, and 1 pound per linear foot of gallery on the shelves. The explosive used was 2½ pounds (1,134 grams) of FFF black powder in first three tests and the same amount of FF black powder in the other four tests.

[b] This test was made to determine the length of flame when only the horse and the first 20 feet of shelves were loaded with dust.

[c] Delayed flame showed also in windows 4 and 5.

[d] Delayed flame showed also in window 5.

Analyses of coal-dust samples taken in tests shown in preceding table.

Test No.	Character of sample.	Moisture.	Volatile combustible.	Fixed carbon.	Ash.
G-2966	Dust before shot	8.00	32.00	54.80	5.20
	Dust after shot	6.60	32.50	54.70	6.20
G-2967	Dust before shot	19.20	25.50	51.00	4.30
	Dust after shot	5.70	24.00	62.00	8.30
G-2968	Dust before shot	19.20	28.00	48.30	4.50
	Dust after shot	15.20	28.50	50.90	5.40
G-2969	Dust before shot	29.70	24.50	41.60	4.20
	Dust after shot	25.70	24.50	44.20	5.60
G-2971	Dust before shot	30.90	23.50	41.20	4.40
	Dust after shot	27.10	24.00	43.10	5.80
G-2972	Dust before shot	11.80	28.00	52.40	7.80
	Dust after shot	4.80	14.50	65.10	15.60
G-2973	Dust before shot	30.70	22.50	42.50	4.30
	Dust after shot	22.10	25.00	45.40	7.50

In the first experiment (G–2966) the total moisture content of the coal was 8 per cent, which is about 6 per cent in excess of the normal moisture content of the standard dust. This amount was insufficient to prevent complete propagation of the flame throughout the gallery.

In the second experiment (G–2967) the moisture content was 19.20 or 17 per cent excess moisture. This also was not sufficient to prevent complete propagation.

Experiment G–2968 was to observe how far the flame would go under the same conditions as in the previous experiment except that only the first three sections of the gallery (20 feet) and the horse were loaded with damp dust. The flame traveled only to the ninth window, equivalent to 57 feet. This experiment was made with the same percentage of moisture (17 per cent excess) as the previous one.

In the fourth experiment (G–2969) the moisture content was raised to 29.70 per cent or 27.70 per cent excess moisture. The result was ignition but not propagation of the explosion, the flame traveling only 30 feet.

Experiment G–2971 was made with dust from the Fairmont district, West Virginia. It was moistened to the extent of 30.90 per cent, or about 29 per cent excess moisture. There was slight ignition, but not propagation. The dust used in this experiment was allowed to dry over night and after being mixed was put back on the shelves. The moisture content then proved to be 11.80 per cent, or 10 per cent of excess moisture. The result was complete propagation.

The final experiment (G–2973) was a repetition of the fifth experiment (G–2971). The moisture content was also practically the same, 30.70 per cent, or about 29 per cent excess. The result was ignition but not propagation.

These experiments, though limited in number, were consistent in results, and indicate that slight dampness is not sufficient to prevent flame propagation by an explosion; that with a high volatile and pure coal such as that used, it is necessary to have a total moisture content approaching 30 per cent to insure that there will be no propagation. This amount of moisture does not make 100-mesh dust seem excessively wet. It can be balled up in the hand, but water is not squeezed out by pressure of the hand. If more moisture is added the critical point is reached, and with about 40 per cent of water the 100-mesh dust and water mixture becomes a coal mud.

These experiments, though they must be accepted as preliminary, give a definite figure for the percentage of moisture that makes coal dust relatively safe under ordinary conditions. Information on this point has been strangely lacking, and it is very important that experiments in this direction be continued.

As a pure 100-mesh coal dust was used in the experiments, a larger amount of moisture probably was needed to render it inert than if it had contained larger particles, or had been less pure, or had been mixed with shale dust. The tests probably represented extreme conditions.

HUMIDITY OF MINE AIR.

NATURAL PRINCIPLES.

SATURATED AIR AT DIFFERENT TEMPERATURES.

The amount of moisture in mine air is of vital consequence in relation to coal dust, as well as in other respects. Aqueous vapor is everywhere present in the atmosphere, whether above ground or in the mine, varying in amount within wide limits.

The term "relative humidity" means the percentage of water vapor present with reference to complete saturation as 100 per cent. When there is complete saturation of aqueous vapor for a given temperature, the "dew point" is reached. Beyond this point of complete saturation, with constant temperature, additional water may be held mechanically in minute drops, as in fog. Hygrometric or psychrometric tables, prepared by Prof. C. F. Marvin, are published and issued by the United States Weather Bureau, and are entitled "Psychrometric tables for obtaining the vapor pressure, relative humidity, and temperature of the dew point." These tables are calculated to small differences in temperature and relative humidity, so that when the difference in the wet and dry bulb thermometer readings is known the figures for the relative humidity and the temperature of the dew point can be read directly with little or no interpolation.

The variation in the amount of water vapor at different temperatures is very striking. For example, at a temperature of 0° F. a cubic foot of completely saturated aqueous vapor weighs 0.481 grain; at 32° the same saturated volume weighs 2.113 grains; at 65°, an ordinary mine temperature in this country, it weighs 6.782 grains; and at 90°, the summer temperature, it weighs 14.790 grains. This is shown in a graphic way in figure 2, which gives the curves of different weights of aqueous vapor per cubic foot at different temperatures and relative humidities.

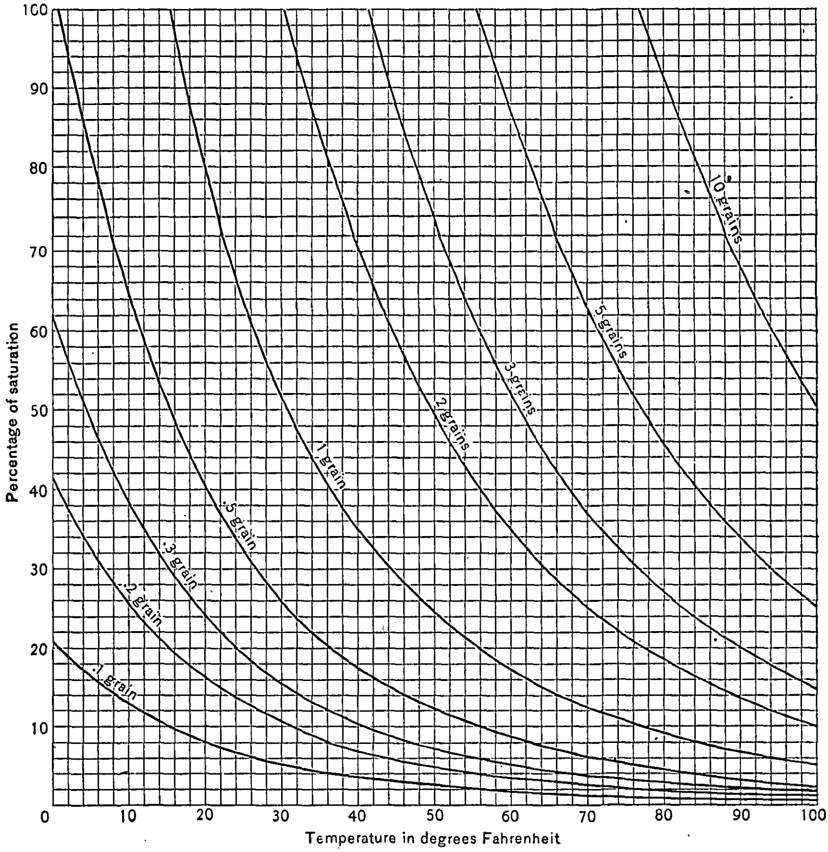


FIGURE 2.—Curves of equal weights of water vapor per cubic foot for varying temperatures and relative humidities when the barometric pressure is 30 inches.

It will be seen, therefore, that when the air and water vapor enter the mine at 0° temperature and are raised to 65° temperature in their course about the mine, unless moisture is picked up on the way the effect is to reduce the relative humidity to a remarkable degree. For instance, if a given space is completely saturated at 0° and contains 0.481 grain of vapor at 65° this weight of water would correspond with only 7 per cent of saturation. This effect is strikingly shown by the curves in figure 2.

AMOUNT OF MOISTURE IN MINE AIR.

The rapidity with which water throws off vapor up to the point of the saturation of the adjacent space is remarkably demonstrated in mines. Technically, the air has not a capacity for moisture, and does not become saturated with it, the aqueous vapor filling a given space with practically negligible reduction in the quantity of air in the same space. The moisture may properly be spoken of as partly or completely saturated, but for brevity it is usual to speak of the "moisture carried by mine air" or of the "relative humidity of the air."

Repeated observations of the amount of moisture carried by mine air, as measured in percentages of the amount of saturation for the observed temperature, have shown that the air current, after traveling about the mine, has a relative humidity of 80 to 100 per cent. In mines in this country the "return" air current near the outlet rarely, except in the dry climate of the Rocky Mountain region, shows less than 90 per cent of saturation, even in a mine that has appeared dry.

A group of observations made in the mines of a considerable number of States and averaged for each State are shown in the following table:

Average of humidity observations during March and April, 1909, in dry and more or less dusty coal mines.

State.	Number of mines.	Series of observations.	Temperature.		Relative humidity.		Water extracted from dust and walls per 100,000 cubic feet of air.	Water extracted from dust and walls in 24 hours.[a]
			Intake.	Return.	Intake.	Return.		
			°F.	°F.	*Per cent.*	*Per cent.*	*Gallons.*	*Gallons.*
Alabama	5	5	71	69	72½	92½	2.27	3,269
Iowa	3	3	46½	56½	61½	93	4.70	6,768
Illinois	8	11	45½	58	60½	91	4.44	6,394
New Mexico	9	14	36	53	57	82	4.57	6,432
Colorado	1	1	72	70	18	85	9.02	12,991
West Virginia	9	9	58½	56	63	94	2.32	3,341
Virginia	1	1	49	57	84	95½	3.04	4,378
Pennsylvania	1	4	48	49	87	91	1.17	1,685
Total	39	48						
Average			53	58½	63	90½	3.94	5,657

[a] The last column is based on the assumption that the average volume of the ventilating currents of the mines was 100,000 cubic feet per minute.

These observations were chiefly made in March and April, 1909, when the conditions contrasted much less than they would in winter. It will be observed that the relative humidity of the return air is nowhere less than 90 per cent, except in the New Mexico and Colorado mines, where the relative humidity of the outside air is normally very low. Therefore the effect of air currents of a relative humidity less than 80 to 90 per cent is to dry out the walls of the passageways through which they pass.

Normally a coal bed is free from water. In many mines water seeps from the surface through troubled ground or "faults," and in some mines artesian flows from the bottom are encountered, but ordinarily there is sufficient clayey matter in the roof and floor to keep out water. In most coal mines, therefore, the presence of moisture, except locally, depends on atmospheric conditions.

EFFECT OF SEASONAL CHANGES OF TEMPERATURE ON MINE AIR.

The warm or hot air of summer contains a large amount of moisture. On entering the mine the air and water vapor are cooled, usually below the dew point, so that precipitation takes place. The walls and roof of the passageways become gradually more and more moist as the summer progresses, and in parts of the mine the walls frequently become beaded with the deposited moisture. In some mines the floor becomes rather wet in the summer months.

On the other hand, in winter the air enters the mine at a temperature usually lower than the mine temperature, which ordinarily ranges in this country from 60° to 65° F. In England and other European countries[a] the outside winter temperature averages higher, but the mine temperatures are also higher, owing to the greater depth of the coal beds. Hence there is the same general contrast of outside and inside temperatures and of relative humidities.

When the air current enters the mine at a low temperature, it carries only a small amount of moisture in the form of vapor, even when the relative humidity is near saturation. As the currents go through the mine and the walls heat up the air and vapor, the relative humidity falls to such an extent that the moisture contained in the walls of the passageways and in the dust lying along them is vaporized and carried away by the air currents. This fact has been noted for many years and by many observers. The danger of dry coal dust has been so much commented upon that it will not again be discussed here until the remedies are considered.

INSTRUMENTS FOR MEASURING ATMOSPHERIC MOISTURE.

SLING PSYCHROMETER.

In the field practically the only method that can be employed to measure the amount of moisture in the air, or the relative humidity, is by observing the temperature of evaporation, which is obtained by noting the difference in temperature between wet and dry bulb

[a] Since the body of this bulletin has been written an important series of papers entitled "Investigation of the drying out of mines and combating the dangers of coal dust," by Bergassessor Forstmann, has been published in Glückauf (January 5 to February 12, 1910). These papers treat of general investigations and of an elaborate series of observations recently made in mines of Germany by a government commission.

thermometers held in a rapid current of air or swung at a rapid rate. The United States Weather Bureau considers that the most reliable instrument for measuring relative humidity by this method is a sling or whirled psychrometer. The standard instrument used by the Weather Bureau consists of a pair of thermometers mounted on a thin metal plate, to which a swivel handle is attached by a loose link. The wet-bulb thermometer projects below the dry-bulb thermometer and the bulb of the former is covered with a thin tight-fitting muslin sack which, just before the observation, is dipped into water. This instrument is described in the psychrometric tables issued by the Weather Bureau.

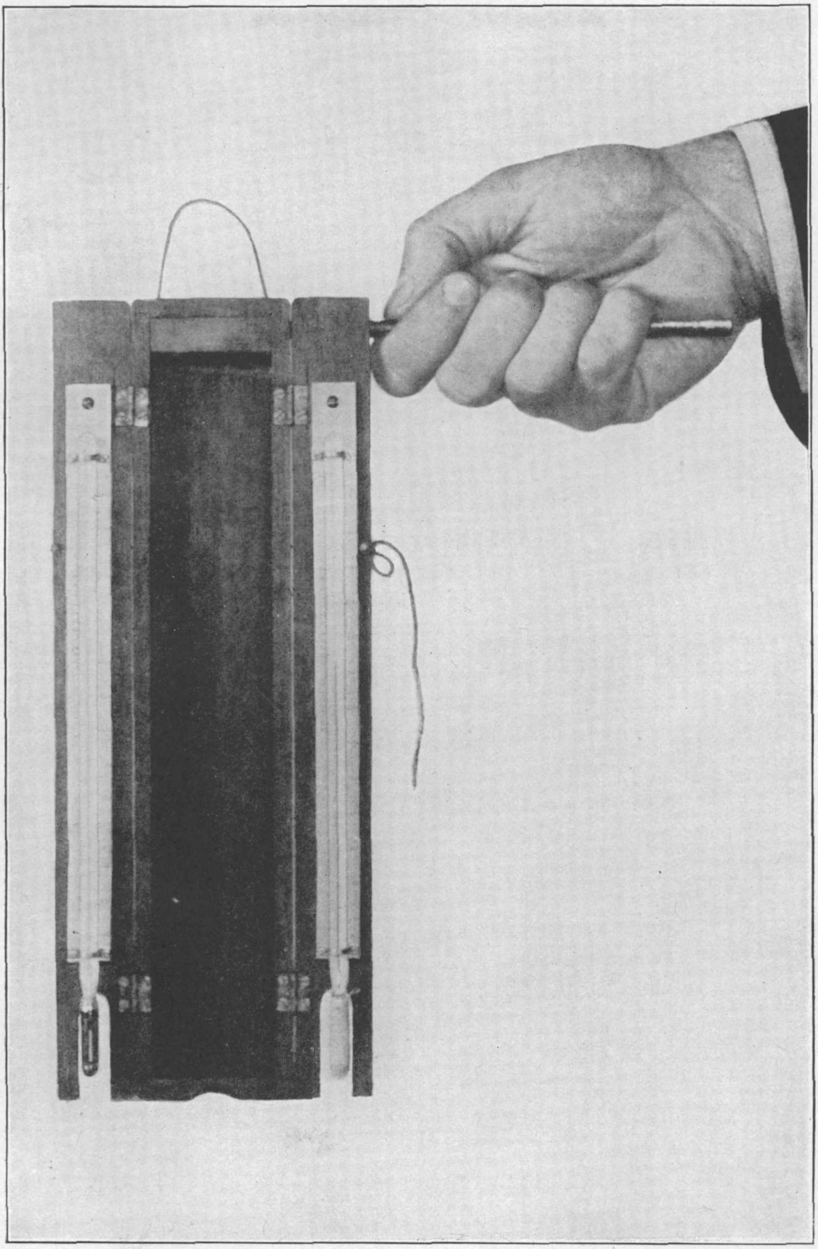
To make standard readings with the sling psychrometer, the speed of the revolving bulb must be 15 feet per second. The psychrometer should be whirled for fifteen or twenty seconds and then quickly read, the wet bulb first. This should be repeated until successive readings of the wet bulb agree closely.

HYGROMETER USED BY GEOLOGICAL SURVEY.

In a mine it is difficult to use the standard sling psychrometer without breaking it. The mining engineers of the United States Geological Survey have been supplied with a psychrometer, more commonly called a hygrometer, in which the thermometers are mounted on the hinged covers of a shallow box. Opposite the thermometer bulbs the covers are slotted to allow free circulation of air. In the use of this hygrometer as designed, the covers are opened wide, held firmly, and swung to and fro, facing the air current. The motion must be violent to obtain the necessary speed. Another method of using it has therefore been improvised by the writer. A hole has been bored through the top of the box parallel with the face of the hinged lids and thermometers and a long pin inserted. The covers are held open by a loop of string passed around the back of the box and attached to a pin. The instrument can thus be whirled like the standard sling hygrometer, with much greater ease than it can be swung. A picture of the instrument with this rearrangement is shown in Plate V. A further improvement could be effected by making the box of aluminum.

STATIONARY HYGROMETER.

There are several types of stationary hygrometers in which the air current is produced by small fans. In another type the hair hygrometer, the rapid change that takes place in the length of a strand of hair with changes in the amount of atmospheric moisture has been utilized to move a pointer by means of a delicately adjusted lever arm. This pointer carries on the end an inking arrangement, so that it can trace a line on sectional paper wrapped on a revolving cylinder



MINE HYGROMETER WITH IMPROVISED SLING ARRANGEMENT.

Showing method of holding for whirling.

turned by clockwork. In this way a permanent and continuous record is obtained.[a] This instrument is sometimes combined with a temperature recorder. Such combination instruments are used by the Fairmont Coal Company at their Monongah mine. They are described in the part of this bulletin by Frank Haas (pp. 150–163).

PRINCIPLE OF WET AND DRY BULB THERMOMETER.[b]

The operation of the wet and dry bulb thermometer is based on the fact that the evaporation of water requires a certain amount of heat. When a current of dry or partly saturated air passes over a wet surface, such as the wet bulb of a thermometer, some of the water is evaporated and carried along by the air in the form of vapor. The absorption of the heat required to evaporate the water causes a cooling of the bulb.

The lower the relative humidity of the air, the more rapid is the evaporation at the surface of the wet bulb, and consequently the lower its temperature. As the bulb is moved through the air its temperature falls to a point where the amount of heat absorbed by evaporation is just equal to that received from the surrounding air. The first quantity of heat is proportional to the rate of evaporation, v. If we assume that the second quantity is proportional to the surface of the bulb, A, and to the difference in temperature between the surrounding air (measured by the dry bulb), and the wet surface, $T_d - T_w$, then $A (T_d - T_w) = av$, where a is a constant.

Dalton found that the rate of evaporation of water is proportional to the surface exposed and to the difference between the pressure of saturated vapor at the given temperature, and the vapor pressure of the surrounding air, $p_1 - p$, and inversely proportional to the barometric pressure, H; then—

$$v = \frac{bA(p_1 - p)}{H}$$

where b is a constant. Hence—

$$A(T_d - T_w) = \frac{abA(p_1 - p)}{H}$$

or,

$$p_1 - p = \frac{H}{ab}(T_d - T_w).$$

Writing $\frac{1}{ab} = c$:

$$p = p_1 - cH(T_d - T_w).$$

[a] Bergassessor Forstmann (Glückauf, January 5 to February 12, 1910) states that the hair hygrometer tried in the recent German experiments did not give consistent results. It was therefore abandoned in favor of swinging wet and dry bulb thermometers.

[b] This explanation and the calculations are given by Dr. J. K. Clement, physicist, of the United States Geological Survey.

This equation is not exact, because neither Dalton's law of evaporation nor the assumption regarding the heat received by the bulb from surrounding objects (Newton's law) is strictly true. The value of c depends on the wind velocity or the rate at which the bulb is moved through the air. For the Schleuder psychrometer $c = 0.00069$. As a matter of convenience, it is customary to use tables in which p is given as a function of $(T_d - T_w)$ and T_d.

METHOD OF MAKING HYGROMETRIC OBSERVATIONS IN MINES AS USED BY ENGINEERS OF THE GEOLOGICAL SURVEY.

The observer must be equipped with a hygrometer, a small bottle of clean water, anemometer, barometer, watch, and tape. Before entering the mine he should make observations of outside atmospheric conditions, selecting, if possible, a point where he will be in the shade, but not where there is any steam or local heat from fires; also, if the shaft or mine opening is an upcast, the point must be selected on the windward side of it in order to obtain correct readings of the relative humidity. Having selected the point, the observer swings the hygrometer, and if there is any wind he should stand so that the instrument receives the wind direct; that is, his body must not obstruct. Having noted the depression of the wet bulb below the dry bulb, he reads the barometer to obtain the atmospheric pressure.

The observer, having gone underground, makes observations at certain stations. It is best, where possible, to select these in advance from the mine map. In general, it is desirable to make observations at the intake and return of each split in the ventilating current, and in particular the main return should be read as close to the outlet as possible.

The method of making all readings underground is the same. After wetting the cloth covering the wet bulb the observer swings the hygrometer, standing sidewise to the current of air, the hygrometer facing the wind. Having repeated the reading a number of times, to insure that the mercury column in the wet-bulb thermometer is depressed as far as it will go,[a] and having recorded the reading, he reads the barometer to obtain the mercurial pressure, which is a combination of the atmospheric pressure and the mine ventilation pressure at that point. The latter pressure is negative or positive according as the fan is exhausting or blowing. Then the velocity of the air current is obtained by means of the anemometer, and the volume of air is obtained by multiplying the velocity by the effective cross section of the passageway. The time of taking the observations at each station, inside and outside, should be recorded, so that the changes in outside atmospheric conditions can be correlated. It is

[a] When the air is below 32° F., the wet-bulb reading remains stationary for some minutes as the water freezes, but as the swinging is continued it will lower proportionately to the temperature and humidity.

important that the cloth of the wet bulb be freshly wetted for each observation.

On going out of the mine it is very important that the observer make hygrometric and barometric readings at or near the station where he made readings on going into the mine and use the average of the two sets to compare with the underground observations or, if the two differ widely, prorate according to the time intervals.

Notation should be made at the different underground stations, and at other intervals, of the amount of dust present on floor ribs, roof, and timbers, also the condition of the dust in the same places as regards moisture. Particular note should be made of moisture drops beading the roof or ribs.

In the light of the preliminary experiments with moistened dust made at the Pittsburg station, as described on pages 50–51, it is advisable to take samples of the dust at certain points and have the moisture and ash contents determined. Such samples should be placed in air-tight receptacles, like glass jars with screw tops and rubber gaskets, at the point of taking, or in special cans, such as are used by the Geological Survey, sealed with insulating tape. Care will have to be exercised in gathering the samples, to have them representative of only that dust which is likely to be thrown into suspension by a violent concussion.

RELATION OF MOISTURE CONTENT TO TEMPERATURE AND PRESSURE OF MINE AIR.

The psychrometric tables issued by the Weather Bureau have already been referred to. The method of using them is explained in connection with the tables as published. One table gives the temperature of the dew point in degrees Fahrenheit for various atmospheric pressures and various depressions of wet-bulb thermometer. This table will not ordinarily be consulted by the mine observer. The tables of more immediate use to him are those giving the relative humidity percentages for different temperatures, pressures, and depressions of the wet-bulb thermometer and the table giving the "weight of a cubic foot of aqueous vapor at different temperatures and percentages of saturation."

The last-mentioned table has been supplemented by one appended below, which gives the number of gallons of water equivalent to the same weight of aqueous vapor in 100,000 cubic feet of air at different temperatures and different degrees of saturation. This unit, 100,000 cubic feet of air, passing in one minute, represents an ordinary mine condition. The other unit (gallons) gives a convenient measure for calculating the amount of water that must be introduced artificially in winter to offset the amount carried out by the return currents.

Figure 2 gives the curves resulting from taking the different weights of aqueous vapor per cubic foot in grams as constants and considering the temperatures and different percentages of saturation as variables.

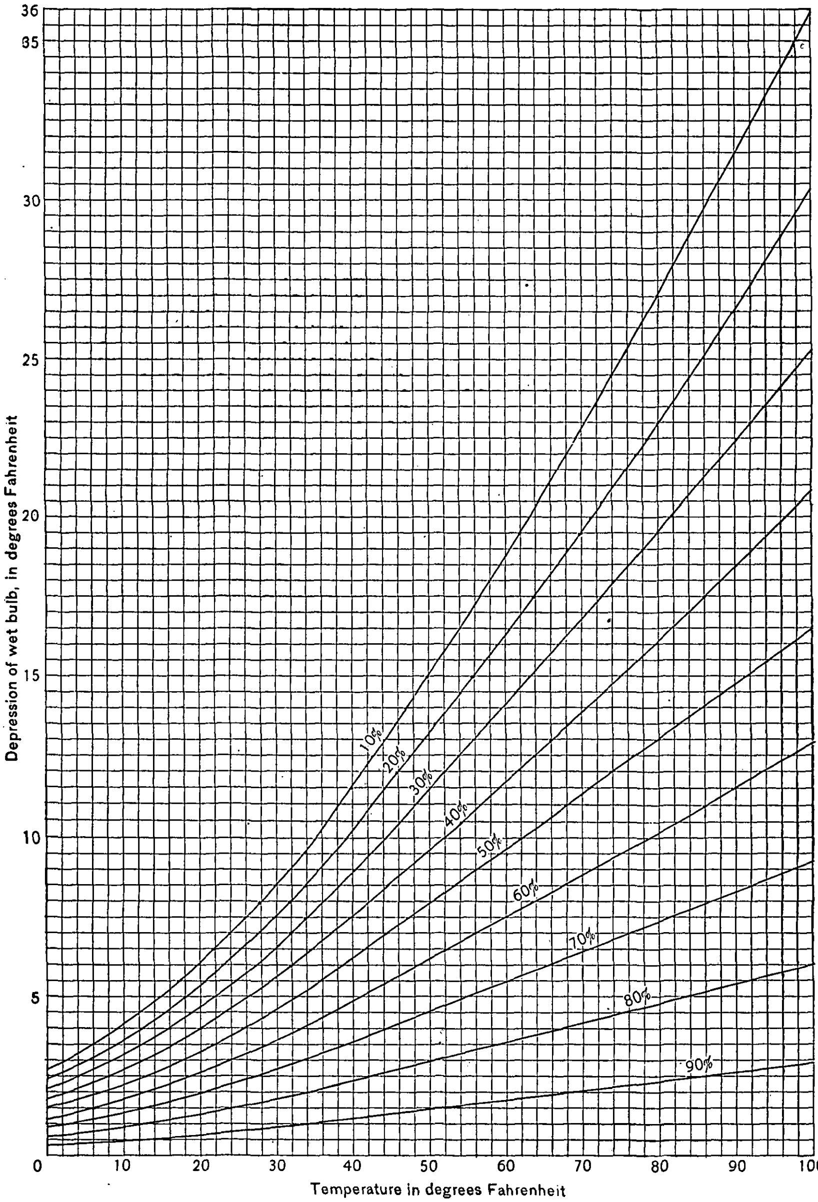


FIGURE 3.—Curves of equal relative humidity for varying temperatures and depressions of wet bulb.

Figure 3 shows the curves derived from considering the different relative humidity percentages as constants and the depression of the wet-bulb thermometer and the temperature as variables when the barometric pressure is 30 inches.

Figure 4 shows the curves resulting from taking different percent-

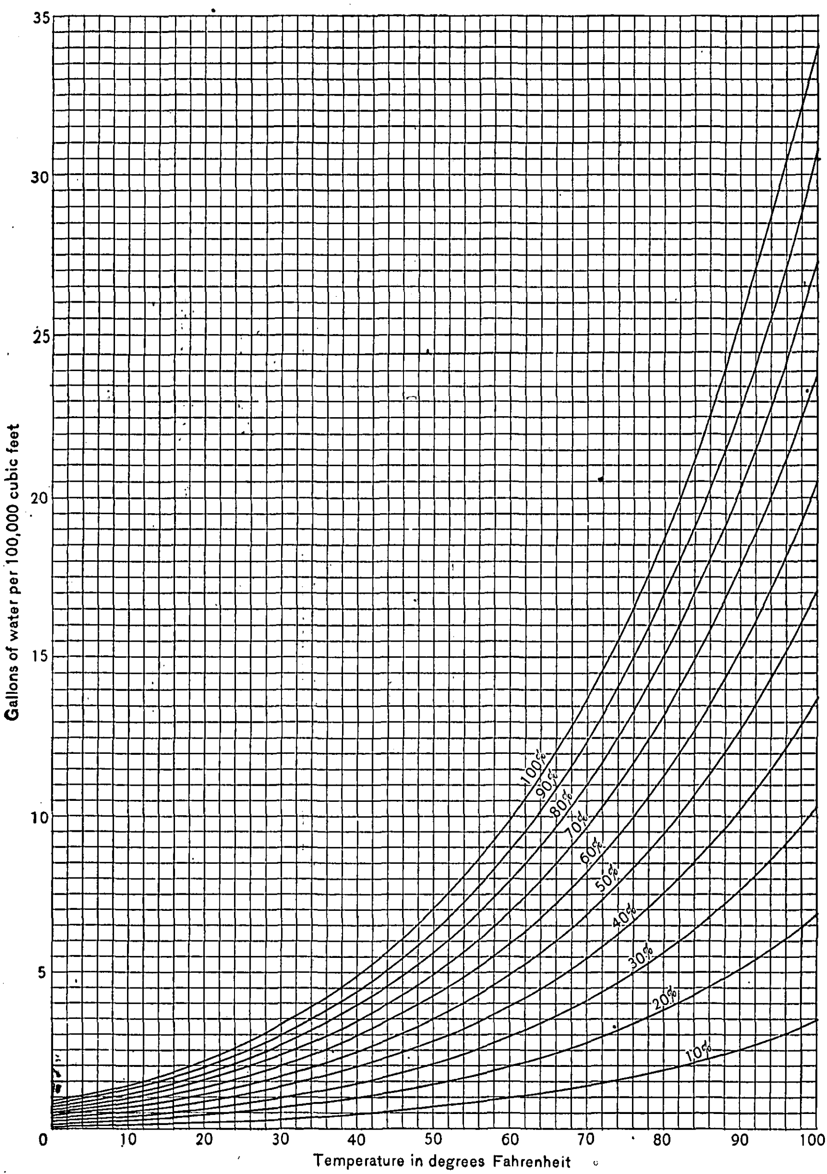


FIGURE 4.—Curves of equal relative humidity for varying temperatures and volumes of water carried.

ages of saturation as constants and the temperatures and gallons of moisture per 100,000 cubic feet of air as variables.

Gallons of water per 100,000 cubic feet of air for specified temperatures and percentages of saturation.[a]

Temperature.	Relative humidity (per cent)—									
	10.	20.	30.	40.	50.	60.	70.	80.	90.	100.
°F.										
−20	0.028	0.057	0.085	0.114	0.142	0.170	0.199	0.227	0.256	0.284
−19	.030	.060	.089	.119	.149	.179	.209	.238	.268	.298
−18	.032	.063	.095	.126	.158	.189	.221	.252	.284	.315
−17	.034	.067	.101	.134	.168	.202	.235	.269	.302	.336
−16	.035	.071	.106	.142	.177	.212	.248	.283	.319	.354
−15	.037	.075	.112	.149	.187	.224	.261	.298	.336	.373
−14	.040	.079	.119	.158	.198	.237	.277	.316	.356	.395
−13	.042	.083	.125	.166	.208	.250	.291	.333	.374	.416
−12	.044	.088	.132	.176	.220	.264	.308	.352	.396	.440
−11	.046	.092	.139	.185	.231	.277	.323	.370	.416	.462
−10	.049	.098	.146	.195	.244	.293	.342	.390	.439	.488
− 9	.051	.103	.154	.206	.257	.308	.360	.411	.463	.514
− 8	.054	.108	.162	.216	.271	.325	.379	.433	.487	.541
− 7	.057	.114	.170	.227	.284	.341	.398	.454	.511	.568
− 6	.060	.120	.180	.240	.300	.359	.419	.479	.539	.599
− 5	.063	.127	.190	.253	.317	.380	.443	.506	.570	.633
− 4	.067	.133	.200	.266	.333	.400	.466	.533	.599	.666
− 3	.070	.141	.211	.282	.352	.422	.493	.563	.634	.704
− 2	.074	.149	.230	.297	.372	.446	.520	.594	.669	.743
− 1	.078	.156	.235	.313	.391	.469	.547	.626	.704	.782
0	.082	.165	.247	.329	.412	.494	.576	.658	.741	.823
1	.087	.173	.260	.346	.433	.519	.606	.692	.779	.865
2	.091	.181	.272	.362	.453	.544	.634	.725	.815	.906
3	.095	.190	.284	.379	.474	.569	.664	.758	.853	.948
4	.100	.199	.299	.398	.498	.598	.697	.797	.896	.996
5	.104	.209	.313	.418	.522	.626	.731	.835	.940	1.044
6	.109	.219	.328	.438	.547	.656	.766	.875	.985	1.094
7	.115	.230	.345	.460	.575	.689	.804	.919	1.034	1.149
8	.121	.241	.362	.482	.603	.723	.844	.964	1.085	1.205
9	.127	.253	.380	.506	.633	.759	.886	1.012	1.139	1.265
10	.133	.266	.399	.532	.665	.797	.930	1.063	1.196	1.329
11	.140	.279	.419	.559	.699	.838	.978	1.118	1.257	1.397
12	.147	.293	.440	.586	.733	.880	1.026	1.173	1.319	1.466
13	.154	.307	.461	.615	.769	.922	1.076	1.230	1.383	1.537
14	.161	.322	.483	.644	.806	.967	1.128	1.289	1.450	1.611
15	.169	.338	.506	.675	.844	1.013	1.182	1.350	1.519	1.688
16	.177	.353	.530	.707	.884	1.060	1.237	1.414	1.590	1.767
17	.185	.370	.555	.740	.925	1.109	1.294	1.479	1.664	1.849
18	.193	.386	.579	.772	.966	1.159	1.352	1.545	1.738	1.931
19	.202	.404	.607	.809	1.011	1.213	1.415	1.618	1.820	2.022
20	.211	.423	.634	.846	1.057	1.268	1.480	1.691	1.903	2.114
21	.222	.443	.665	.886	1.108	1.329	1.551	1.772	1.994	2.215
22	.232	.464	.696	.928	1.160	1.392	1.624	1.856	2.088	2.320
23	.243	.486	.728	.971	1.214	1.457	1.700	1.942	2.185	2.428
24	.254	.508	.762	1.016	1.270	1.523	1.777	2.031	2.285	2.539
25	.266	.531	.797	1.062	1.328	1.593	1.859	2.124	2.390	2.655
26	.278	.556	.834	1.112	1.390	1.667	1.945	2.223	2.501	2.779
27	.291	.581	.872	1.162	1.453	1.743	2.034	2.324	2.615	2.905
28	.304	.607	.911	1.214	1.518	1.821	2.125	2.428	2.732	3.035
29	.317	.634	.952	1.269	1.586	1.903	2.220	2.538	2.855	3.172
30	.331	.662	.994	1.325	1.656	1.987	2.318	2.650	2.981	3.312
31	.346	.692	1.039	1.385	1.731	2.077	2.423	2.770	3.116	3.462
32	.362	.724	1.085	1.447	1.809	2.171	2.533	2.894	3.256	3.618
33	.376	.751	1.127	1.502	1.878	2.254	2.629	3.005	3.380	3.756
34	.390	.780	1.171	1.561	1.951	2.341	2.731	3.122	3.512	3.902
35	.405	.810	1.215	1.620	2.026	2.431	2.836	3.241	3.646	4.051
36	.421	.841	1.262	1.682	2.103	2.524	2.944	3.365	3.785	4.206
37	.437	.873	1.310	1.746	2.183	2.620	3.056	3.493	3.929	4.366
38	.453	.906	1.359	1.812	2.265	2.718	3.171	3.624	4.077	4.530
39	.470	.940	1.410	1.880	2.351	2.821	3.291	3.761	4.231	4.701
40	.488	.976	1.463	1.951	2.439	2.927	3.415	3.902	4.390	4.878

[a] The table is devised on the assumption that if the water vapor in 100,000 cubic feet of air at any given temperature and percentage of saturation were condensed, it would be equivalent to a certain number of gallons of water at that temperature. For temperatures of 32° or under, the figures are given on the assumption that the vapor is equivalent to a certain volume of water at 32°.

Gallons of water per 100,000 cubic feet of air for specified temperatures and percentages of saturation—Continued.

Temperature.	Relative humidity (per cent)—									
	10.	20.	30.	40.	50.	60.	70.	80.	90.	100.
41	0.506	1.012	1.518	2.024	2.530	3.035	3.541	4.047	4.553	5.059
42	.525	1.049	1.574	2.098	2.623	3.148	3.672	4.197	4.721	5.246
43	.544	1.088	1.632	2.176	2.720	3.263	3.807	4.351	4.895	5.439
44	.564	1.128	1.692	2.256	2.820	3.383	3.947	4.511	5.075	5.639
45	.585	1.169	1.754	2.338	2.923	3.507	4.092	4.676	5.261	5.845
46	.606	1.212	1.818	2.424	3.030	3.635	4.241	4.847	5.453	6.059
47	.628	1.256	1.883	2.511	3.139	3.767	4.395	5.022	5.650	6.278
48	.651	1.301	1.952	2.603	3.254	3.904	4.555	5.206	5.856	6.507
49	.674	1.348	2.022	2.696	3.370	4.044	4.718	5.392	6.066	6.740
50	.698	1.396	2.094	2.792	3.490	4.187	4.885	5.583	6.281	6.979
51	.723	1.446	2.169	2.892	3.615	4.337	5.060	5.783	6.506	7.229
52	.749	1.497	2.246	2.995	3.744	4.492	5.241	5.990	6.738	7.487
53	.775	1.550	2.325	3.100	3.876	4.651	5.426	6.201	6.976	7.751
54	.802	1.605	2.407	3.209	4.012	4.814	5.616	6.418	7.221	8.023
55	.831	1.661	2.492	3.322	4.153	4.984	5.814	6.645	7.475	8.306
56	.859	1.718	2.578	3.437	4.296	5.155	6.014	6.874	7.733	8.592
57	.889	1.778	2.667	3.556	4.446	5.335	6.224	7.113	8.002	8.891
58	.920	1.840	2.760	3.680	4.600	5.519	6.439	7.359	8.279	9.199
59	.952	1.903	2.855	3.806	4.758	5.710	6.661	7.613	8.564	9.516
60	.984	1.969	2.953	3.937	4.922	5.906	6.890	7.874	8.859	9.843
61	1.018	2.036	3.054	4.072	5.090	6.107	7.125	8.143	9.161	10.179
62	1.053	2.105	3.158	4.210	5.263	6.315	7.368	8.420	9.473	10.525
63	1.088	2.176	3.264	4.352	5.440	6.528	7.616	8.704	9.792	10.880
64	1.125	2.250	3.375	4.500	5.625	6.749	7.874	8.999	10.124	11.249
65	1.163	2.325	3.488	4.650	5.813	6.976	8.138	9.301	10.463	11.626
66	1.202	2.403	3.605	4.806	6.008	7.209	8.411	9.612	10.814	12.015
67	1.242	2.483	3.725	4.966	6.208	7.449	8.691	9.932	11.174	12.415
68	1.282	2.565	3.847	5.130	6.412	7.694	8.977	10.259	11.542	12.824
69	1.325	2.650	3.974	5.299	6.624	7.949	9.274	10.598	11.923	13.248
70	1.369	2.737	4.106	5.474	6.843	8.212	9.580	10.949	12.317	13.686
71	1.413	2.826	4.240	5.653	7.066	8.479	9.892	11.306	12.719	14.132
72	1.459	2.919	4.378	5.838	7.297	8.756	10.216	11.675	13.135	14.594
73	1.507	3.013	4.520	6.026	7.533	9.040	10.546	12.053	13.559	15.066
74	1.556	3.111	4.667	6.222	7.778	9.334	10.889	12.445	14.000	15.556
75	1.605	3.211	4.816	6.422	8.027	9.632	11.238	12.843	14.449	16.054
76	1.657	3.314	4.971	6.628	8.285	9.941	11.598	13.255	14.912	16.569
77	1.710	3.420	5.130	6.840	8.550	10.259	11.969	13.679	15.389	17.099
78	1.764	3.529	5.293	7.057	8.822	10.586	12.350	14.114	15.879	17.643
79	1.820	3.640	5.461	7.281	9.101	10.921	12.741	14.562	16.382	18.202
80	1.878	3.755	5.633	7.510	9.388	11.266	13.143	15.021	16.898	18.776
81	1.937	3.873	5.810	7.746	9.683	11.619	13.556	15.492	17.429	19.365
82	1.997	3.994	5.991	7.988	9.986	11.983	13.980	15.977	17.974	19.971
83	2.059	4.119	6.178	8.238	10.297	12.356	14.416	16.475	18.535	20.594
84	2.123	4.246	6.370	8.493	10.616	12.739	14.862	16.986	19.109	21.232
85	2.189	4.378	6.566	8.755	10.944	13.133	15.322	17.510	19.699	21.888
86	2.256	4.513	6.769	9.026	11.282	13.538	15.795	18.051	20.308	22.564
87	2.325	4.651	6.976	9.302	11.627	13.952	16.278	18.603	20.929	23.254
88	2.396	4.793	7.189	9.586	11.982	14.378	16.775	19.171	21.568	23.964
89	2.469	4.939	7.408	9.878	12.347	14.816	17.286	19.755	22.225	24.694
90	2.544	5.088	7.632	10.176	12.720	15.263	17.807	20.351	22.895	25.439
91	2.621	5.241	7.862	10.483	13.104	15.724	18.345	20.966	23.586	26.207
92	2.699	5.399	8.098	10.798	13.497	16.196	18.896	21.595	24.295	26.994
93	2.780	5.560	8.340	11.120	13.900	16.680	19.460	22.240	25.020	27.800
94	2.863	5.726	8.539	11.452	14.315	17.177	20.040	22.903	25.766	28.629
95	2.948	5.895	8.843	11.791	14.739	17.686	20.634	23.582	26.529	29.477
96	3.035	6.069	9.104	12.138	15.173	18.208	21.242	24.277	27.311	30.346
97	3.124	6.248	9.372	12.496	15.620	18.743	21.867	24.991	28.115	31.239
98	3.216	6.431	9.647	12.862	16.078	19.294	22.509	25.725	28.940	32.156
99	3.310	6.620	9.929	13.239	16.549	19.859	23.169	26.478	29.788	33.098
100	3.406	6.812	10.217	13.623	17.029	20.435	23.841	27.246	30.652	34.058

REMEDIES FOR COAL DUST.

REVIEW OF REMEDIES PROPOSED.

As soon as the dangers of dry coal dust became recognized, suggestions for remedies began to appear. The British accidents in mines commission in its final report in 1886 (p. 48) stated:

> The removal of accumulating dust is practiced to some extent here and there; but this measure is obviously attended by many difficulties, and even if carried out as thoroughly as practicable, it would generally only be the main roads that could be kept fairly free from dust. * * * If, however, * * * the mine ways [are kept] as free from dust as practicable, and the removal of the principal part of dust accumulations from the working places can be supplemented by the application of some efficient method of rendering the remaining dust innocuous in the presence of a blown-out shot, there can be no doubt that the dangers arising from coal dust will be very greatly reduced, if not rendered altogether insignificant.

Since the time of the foregoing report, numerous means have been suggested, and some tried out, to secure immunity from the coal-dust danger. A summary of the methods that have already been put forward follows:[a]

1. Loading and cleaning up dust.
2. Sprinkling from water cars.
3. Application of calcium chloride and other deliquescent salts.
4. Sprinkling and washing down with hose and nozzle.
5. The use of pipe lines and permanent sprinklers.
6. Humidifying the intake air current by steam sprays.

The foregoing comprise the general methods of rendering coal dust inert. There are other methods which contemplate the prevention of explosions from blown-out shots and the limiting of initial explosions. These may be summarized as follows:

7. The use of quick-flaming or short-flaming ("permissible") explosives.
8. Coating the walls and floor of the passageways with rock dust, either wholly or in zones.
9. Limiting the extent of explosions by the construction of brick or concrete linings of definite length and intervals and keeping them perfectly clean.

LOADING AND CLEANING UP DUST.

Loading dust into pit cars and hauling it out of the mine does not require extended explanation. The method is obvious and has been more or less practiced in maintenance of roadways. In rooms of the ordinary room-and-pillar system the fine coal and dust is seldom

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[a] Two new methods have been brought out recently in Germany. One, which aims at preventing the formation of dust at the face, is to force water at high pressure into the coal seam through long holes, drilled in advance of the face. This method does not seem applicable in room-and-pillar work. Another method recently patented, called the Kruskopf process, employs a viscous paste applied to all surfaces. It is stated that a recent experiment in a Westphalian mine showed that the "walls remained damp three thousand hours after the application of the paste, but they dried up within six hours when water was used." (Scientific American, May 21, 1910.) See also p. 149.

wholly loaded out. While the coal may be carefully shoveled up at the face, the fine coal, thrown back into the "gob" by shooting, usually becomes so mixed with dirt or rock that it would be difficult to gather it and send it out in pit cars without undue expense.

In some sections of this country the practice is to require the miner to leave the cuttings in the gob, particularly when the cutting is done in mixed coal and shale bands. This is certainly not good practice. It may save the quality of the screenings from injury at mines where there is not a washery to wash out the clay or shale, but it leaves a dangerous condition within the mine, increasing not only the chances of a dust explosion, but also the risk of gob fires.

Cleaning up fine dust after the coarser small coal has been shoveled out is far more difficult than the latter and is practically impossible on a rough uneven floor. If a broom is used, this merely moves the finer and more dangerous dust to other settling points. A possible method of sweeping which may be developed in future is the use of a modified form of house vacuum cleaner; though recent preliminary trials in England have not been successful except where the passageway was lined smoothly with brick or concrete.

SPRINKLING FROM WATER CARS.

Sprinkling the roadways by means of water cars was the earliest method of watering coal dust. At first the water was thrown out by means of a bucket from a plain tank car or let dribble from the car in the middle of the roadway. The latter primitive plan is still used in many mines. The next step was to put a sprinkling pipe on the rear of the water car—that is, a pipe with perforations. Necessarily, only the roadway floor can be sprinkled with so slight a water head, and though this means when frequently employed prevents some dust from being raised by the traffic it does not reach the dangerous dust on the walls and timbers.

The next advance was to place a force pump on the cars, or to use air compressed in the top of the tank, to force the water out under such pressure that the roof and sides could be sprinkled as well as the floor. This method is much employed to-day at many of the leading mines. If carried out systematically and constantly it is an effectual method, but if used only occasionally, say once or twice a week, very little good is accomplished. Dust is extremely difficult to wet and the drops of water are not absorbed unless the dust is already more or less damp. If the drops remain exposed, they are quickly absorbed by the air currents and the road becomes dry. There are practical difficulties in using water cars efficiently; thus, to sprinkle each road once or twice a day would seriously interfere with the hauling of coal. On the night shift the tracks and sidings are occupied by "loads" and "empties," so it is difficult to get the water cars through the roadways, and particularly to water the partings or sidings, which are usually the most dusty points. It therefore requires special planning and efficient administration to obtain satisfactory results.

CALCIUM CHLORIDE AND OTHER DELIQUESCENT SALTS.

The rapid drying out of dust which had been sprinkled and the damage wrought to some mine roofs and ribs by sprinkling intermittently, led some of the early investigators to experiment with hygroscopic salts.

In 1879, Professor Stokes suggested the use of calcium chloride. Professor Abel, giving evidence before the accidents in mines commission in 1881, said:

> It might possibly be desirable to try for watering purposes a solution of calcium chloride * * * which has been found very useful in keeping ground moist in a current of air.

The commission, in its final report in 1886 (p. 49) stated:

> The generally elevated temperature of mines combines with the desiccating effect of the more or less rapidly circulating air currents to counteract the amount of protection obtainable even by frequent liberal watering. Hence attempts have been made within the last six or seven years to promote the retention of water by coal dust, by the application to it of hygroscopic or normally deliquescent bodies. Crude salt was tried in the first instance, and in 1879 Professor Stokes suggested the watering of the dust with a solution of calcium chloride, a highly hygroscopic salt which had been successfully applied in connection with street watering * * * but its trial in some dry deep mines in South Wales and also in the Jablin pits in France was not attended with success; the highly deliquescent salt actually crystallized out, consequent upon the rapid evaporation of the water in the warm air currents. Some amount of success appears however to have attended the application, in mines in North Staffordshire, of crude or refuse salt; this contains a very notable proportion of the magnesium chloride, which is, if anything, more hygroscopic in its character than the calcium salt. In an interesting discussion which followed Mr. Robert Stevenson's communication of his favorable experience in this direction to the North of England Institute of Mining Engineers, the view received some support that the deliquescent salts would be most operative if used in admixture with sodium chloride, as is the case in crude or rock salt. The proportion of crude salt which Mr. Stevenson had found effective in maintaining the dust sufficiently moist to prevent its flying was 9 tons per 500 yards of 6-foot roadway, applied once weekly for the first month and once a month afterwards.

The method was not mentioned in the report of 1894 of the royal commission on accidents from coal dust in mines. It apparently attracted very little attention until the last few years, when the discussion of the use of salts was revived.

Mr. Henry Hall, British inspector of mines, in a recent article[a] says:

> On February 22, 1908, a length of 285 feet of tunnel at St. Helens, England, was treated with a 40 to 45 per cent solution of calcium chloride. The floor of the tunnel

[a] Coal and Coke Operator, Pittsburg, Pa., May 27, 1909, p. 375.

was very dusty, the dust (chiefly stone dust) rising higher than the men's knees as they walked along. The solution was put on with a whitewashing machine, using about 8 gallons of solution to 30 linear feet of road (road 9 feet wide). The surface of the dust was thus dampened, but under the crust there was very little effect, and dust raised by the traffic inby continued to travel, carried by the wind, over the treated portion. Considering that the dust was not removed before the application, but lay some 3 inches thick, the result was fairly satisfactory, and for three months the road could be traveled with comfort. * * * On April 14, 1908, 225 feet in the main return tunnel was treated with 90 gallons of 48 to 50 per cent solution of calcium chloride, the dust having been previously cleaned off. This application kept the road clear of dry dust for three months, and at the present time (August 22, 1908) the effect is still visible. * * * The solution when applied to side or roof had the same damaging effect as water. On May 28, 1908, 330 pounds of calcium chloride, previously ground to a fine powder, was sprinkled on the floor of the back brow for a distance of 249 feet, no dust having been removed. It was reported as being wet and no dust rising on the following day. The writer saw this road on July 6 and the effect was still visible. Judging from this experiment, one application for every three months would be ample. The depth, from the surface, of this underground road is but 500 feet. The powdered calcium chloride was thrown on dry by hand, 350 pounds being put on 2,241 square feet. On July 14, 282 square [a] feet was treated with 448 pounds of dry powdered calcium chloride. The dust was cleaned away from 60 feet of this road; the remaining 222 feet not being cleaned. This road was reported to be wet the next day and the writer saw it on July 16. * * * The writer saw a team brought out by the pony and no dust was raised. Previous to the application, dust traveled some 60 feet ahead of the pony. The writer saw this part again on August 6 and found it to be still quite satisfactory and apparently likely to continue so for some time longer. * * * The writer believes the cost to be about 50 shillings ($12.50) a ton (dry powdered calcium chloride), but there would be a great saving in labor in its application to the roads as compared with either plain water or any solution, and no capital outlay for pipes, barrels, hose, sprinklers, etc., is needed. Probably the cost per 100 yards by 9 feet wide would be something like 13 shillings ($3.25), but it must be remembered that plain water would have to be applied almost daily, whereas the calcium chloride would apparently be effective for three months.

Mr. Hall then comments on the superior hygroscopic property of calcium chloride as compared with common salt. In conclusion he remarks that the test would require to be carried much further than he had carried them. The conditions vary much in different mines. So far as he had gone, the impression left on his mind was that dust accumulated in the main roadways at a much smaller rate than has been generally observed. He agreed with the observations of Mr. Rhodes, as to the effect of occasional spraying with water—50 or 60 yards in advance of the sprays the conditions were generally just as they were before the spraying was done.

Mr. Hall gives a table of analyses of dust from the mine where the tests were made, but he does not give the moisture content. The most striking feature of the analyses is the high ash of the samples, ranging from 17 to 67 per cent. It is evident that the coal dust was much diluted with rock or shale dust.

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[a] Author probably intended this to be linear feet of roadway.

In a recent article [a] Mr. Joseph Virgin, the superintendent of the Plymouth Coal Company, Plymouth, W. Va., says:

Believing that calcium chloride would act satisfactorily * * * on February 8, 1909, we placed 3 barrels (1½ tons) * * * on about 500 feet of heading, the latter being 8 feet wide; we distributed the salt like sowing seed broadcast. The dust on the tracks was about 3 inches deep and on the débris one-eighth inch. All was covered with salt * * * in twenty-four hours, the fine coal was moist, and in two days the dust was quite damp and would stick to the hand like wet gunpowder. The dust remained damp for more than a month. On April 8, 1909, this heading was cleaned up.

Several mines in the Pocahontas region of West Virginia, at Marytown and near Elkhorn, and several mines in the Pittsburg district of Pennsylvania used calcium chloride during the winters of 1908–9 and 1909–10 with reported favorable results.

Some tests with crude calcium chloride,[b] a by-product of chemical manufactories, were made in the winter of 1909–10, with the cooperation of the writer, in the Catsburg mine of the Monongahela Consolidated Coal and Coke Company, working the Pittsburg seam, in Washington County, Pa. Two adjoining "butt" entries, very dry and dusty, about 2 miles in from the drift mouth, but on a split of air drawn from an air shaft only 2,500 feet distant, were selected for the experiments.

The reason for the dryness of these roads is apparent from the hygrometric readings, which were made on January 14, 1910. The calculated results follow:

Hygrometric readings in Catsburg mine.

	Dry bulb.	Wet bulb.	Relative humidity.	Water per 100,000 cu. ft. of air.
	°F.	*°F.*	*Per cent.*	*Gallons.*
Intake air	38	36	83	3.76
At entrance to district 78, butt entry	47½	44½	79	5.05
Middle of district	50	48	87	6.07
Return of district	58½	57	91	8.51

There is therefore absorbed from this one district 3.46 gallons of water per 100,000 cubic feet of air circulated. The volume of the split is 3,750 cubic feet per minute. The extraction of moisture from this small district, assuming that the hygrometric reading represented average winter conditions, would be 187 gallons per twenty-four hours.

Three areas were treated, each about 400 feet long, separated by untreated areas.

In the first, the road had been cleaned up to the level of the top of the ties and watered about one week before the application of calcium

[a] Dust problem in coal mines: Eng. and Min. Jour., October 9, 1909, p. 734.

[b] Composed, according to an analysis by A. C. Fieldner, chemist, of the Survey, of 56 per cent $CaCl_2$, 11 per cent NaCl, and 32.70 per cent H_2O.

chloride, which was made February 27. The calcium chloride was spread on dry to the amount of 1 pound per linear foot of the entry, which was from 8 to 9 feet wide. The road was ballasted with coal and shale fragments to the depth of the ties and from 6 to 10 inches deep along the sides.

In the second area the coal dust had not been cleaned or watered for a long time before the application, which was made on February 12, and the fine coal and shale dust was thick along the track and on the sides. This was treated with the dry calcium chloride to the same amount as the first section. The calcium chloride had been received in large drums, and was cemented in a solid mass, which had to be broken down by hammer to pieces about one-half inch in size and less. In both the dry treatments the roof and ribs were not considered. As it was a "butt" entry, the smooth, bright coal "faces" parallel with the road gave no lodgment for dust. The roof, which was shale and top coal, did not require timbering. The roads had been so dry that dust was raised in walking.

In the third area, also 400 feet long, the calcium chloride was applied February 14. It was in solution, containing 8 per cent of calcium chloride by weight. The entry was sprinkled by means of a force-pump sprinkling car, which sprinkled the top, sides, and floor. The total amount of calcium chloride put on was 1 pound per linear foot with 12½ times as much weight of water. The watering was done not only on the floor, but also on the ribs and roof.

On March 7 an investigation of these areas was made by the writer. In the first area the coal dust in the roadway was damp to the touch and would pack in the hand. This was eight days after treatment with the dry calcium chloride. There was an entire absence of dry dust. The sides and roof felt dry, but, as stated, these were not treated and had been practically free from dust.

In the second area, twenty-three days after treatment with the dry calcium chloride, the floor dust was damp and sticky and was more or less packed in the roadway. There was an entire absence of dry dust.

In the third area, treated with the wet solution February 14, the road dust was more or less dry. When kicked it would rise as float dust. It did not seem as dry as it had been before the application, but the effect of the calcium-chloride treatment had been practically lost. The ribs and roof were also dry, but as they were smooth no dust had collected.

Samples were gathered of the dry road dust of the three areas before their treatment, and on March 7 after treatment. These samples contained all sizes of fragments of coal and shale. The portion that passed through a 20-mesh screen was considered dust, and the remainder was rejected. In the samples from the areas that had been treated the particles were stuck together and could not be screened until air dried. The moisture in the whole sample from the area treated eight days before (first area) was 10.57 per cent, or about 8.5 per cent excess over the normal moisture content of the air-dried coal. The moisture in the sample for the area treated twenty-three days before (second area) was 7.20 per cent, or about 5 per cent excess over normal. Of the former sample only 25 per cent passed through a 20-mesh screen; of the latter, 12 per cent. Experiments with these samples indicated that the undersize retained after preliminary drying three times as much water as the oversize. If this proportion also holds in the preliminary drying, the undersize from the first area contained 14 per cent of moisture and the undersize from the second area contained 21 per cent. The plastic condition of the samples indicated at least these amounts of moisture. It was the moisture in the finer sizes of dust, as well as the sticky nature of the salt, that caused the adhesive quality.

It is evident that a determination of the humidity of the air in areas treated with calcium chloride does not provide a test of the efficacy of the latter in preventing the formation of loose, dry, dangerous coal dust. The calcium chloride through its affinity for water draws the water vapor from the atmosphere. The latter would therefore show a deficiency (too small to be measurable) rather than an excess of moisture. Hence the success or failure of the treatment must be judged by the physical aspect of the dust or by chemical determinations supplemented by tests in an experimental gallery.

The experiments in the Catsburg mine can not be considered conclusive, but it is interesting to compare the results obtained by the dry and the wet treatments; the application of the dry calcium chloride to the floor dust appeared to be very effective, under severe conditions, inasmuch as rooms were turned off the butt entry and there was a constant dribbling of fresh coal along the road. The condition of the floor, however, was such that the new dust as it was crushed under foot packed down into the general mass.

At first thought it appears singular that the application of the calcium chloride in solution was less effective. The explanation may be that on account of the dryness of the dust the solution quickly sank down into the large mass of coal dust, which was deeper than the thickness of the ties, and the effect on the surface was thus lost, whereas the dry calcium chloride, being more or less coarse, remained on the surface and absorbed the moisture from the air, causing a stickiness that tended to pack the dust together. It will, of course, be necessary to have more data before positive conclusions can be reached as to the advisability of the use of calcium chloride under varying mine conditions. If as successful as it promises to be on the floor or gobs of mines it would seem to be a system peculiarly adapted to the mines in the arid Rocky Mountain district, where there is a scarcity of water for wetting the dust and where an unusually large amount is needed on account of the dryness of the air.

Crude calcium chloride can be procured in granulated form. The price in the leading cities in 1910 varies from $14 to $18 per ton, put up in wood barrels. If preferred it can be procured in a 40 per cent solution in iron drums.

SPRINKLING AND WASHING DOWN WITH HOSE AND NOZZLE.

The method of using pipe lines through a mine with connections at intervals for attachment of hose was introduced in England and used to a slight extent after the report, in 1886, of the accidents in mines commission. In the same year W. N. and J. B. Atkinson published their book "Explosions in coal mines." In their suggestions for remedies they anticipated some of the later developments. They state that water tubs of the ordinary kind are ineffectual and that the use of water pipes, with cocks at short intervals, and hose is a better system; and they advise that where watering causes trouble by affecting the roof or floor, the mine may be divided into sections by arching entries, whitewashing the arched sections, and sweeping up the bottom dust. They add: "Perhaps 100 yards (of lining) would suffice."

In Germany in consequence of the report of the Prussian fire-damp commission of 1885 watering, chiefly by hose sprinkling, was introduced into mines. This system has grown to the exclusion of others. Watering became compulsory in Germany in 1900. The mining department now insists that the roof and walls of the gangways be not merely sprinkled but washed by a stream from a hose.[a]

In England the use of the hose and nozzle has not become at all general. The mining men generally consider that it is too severe on the roof and walls; that heavy falls of roof and heaving of the floor would be caused.

In the United States the system of watering by hose and nozzle has been employed in the coal mines of Utah since the Scofield disaster of May 1, 1900, and it is now required by the Utah mining law. The conditions for the use of this method in the Utah field are very favorable, as the floor and roof are generally sandstone and are therefore not affected by the direct application of water. The method has been used only to a very limited extent in a few mines in Pennsylvania and other eastern States.

Wherever the method can be employed it is undoubtedly an efficacious one, particularly if the water pressure is good, but it requires

[a] About the time sprinkling was begun extensively in Germany the worm disease called ankylostomiasis broke out widely among the mine workers of Westphalia. It had been known much earlier, but the fact that the severe outbreak occurred simultaneously with more extensive watering led to the belief that that practice was the sole cause. Undoubtedly humid warm air fosters the disease, but by the adoption of rigid sanitary precautions the epidemic was overcome and although the watering has been continued the disease has been almost completely stamped out.

constant effort and the employment of men to go continually from point to piont. It has the merit that water can be effectually applied where most needed, and it is not interfered with by the haulage system. Undoubtedly it requires a strong roof and a floor that will not heave from excess of water; otherwise the cost of maintaining the roadways is high.

PERMANENT SPRINKLERS.

The use of permanent sprinklers to dampen coal dust began in England shortly after the report of the royal commission of 1886. It is spoken of in a paper read in 1887 by Professor Abel.[a] He mentions the Harris Navigation colliery, in which "the temperature was reduced 6 degrees" by water sprays. He also refers to the system of water and compressed-air sprays invented by Mr. Henry Martin, who appeared before the royal commission in March, 1892, and asserted that he had employed the system since 1886 in the Dowlais collieries. Mr. Martin stated that the sprays used air compressed to 45 pounds and water under a pressure of 90 pounds to the square inch. The water was used under high pressure, so that if the air compressor stopped for any reason a fine spray might be produced with water alone. The effect of using compressed air was to make the spray very light, so that it would travel a long distance in the air current. Mr. Martin stated that the sprays were located 50 to 80 yards apart, although it is not strictly necessary to have them less than 200 yards apart. Where they were nearer together it was not necessary to use each one continuously. Mr. Martin said that the system incidentally improved the ventilation and temperature of the mine. They used the sprays at night but not during the day. He submitted a list of hygrometric readings taken 20 to 60 feet distant from each of the sprays to show that practically complete vapor saturation was obtained in every instance.

There does not appear to have been any wide extension of the use of compressed air and water sprays in mines, but the system has been applied in cotton mills in New England to humidify the air, both for the health of the employees and for the effect that it has upon the weaving process. In mines of the United States some attempt has recently been made to introduce such sprays, but as yet they have not been used to any considerable extent.

At the Pittsburg station, in the experiments carried on in the explosion gallery to try the effect of humidity in rendering coal dust inert, compressed air and water sprays were employed. As they were installed, the water has very little head, a few pounds only; the air is under 35 pounds compression. A very fine spray like a mist is

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[a] Abel, Frederick, Mining explosions and their prevention, 1889, pp. 116, 182.

produced. The spray heads are of the kind employed in cotton mills, and are too small and fragile for mine use. In mines where compressed air is available underground the system has much merit.

Plain water sprays have been much used in the coal mines of Wales. In certain collieries they are used continuously day and night, and the effect is excellent. In addition to the regular station sprays, special sprays have been used at the ends of partings or sidings. When a trip of cars leaves the siding, the spray is turned on and drenches the top of the car. Sprays of this kind should throw a larger volume of water than the station sprays. They serve a most useful purpose in washing fine dust that may have settled on top of the coal down into the body of the car, so that the sweeping of the ventilating current over the tops of the cars does not carry away fine coal.

In this country water sprays have been used only to a moderate extent until quite recently. In the Rock Island Coal Company mines in Oklahoma water sprays have been extensively introduced by Mr. Carl Scholz, who has written a number of papers on the subject, among others one on the effect of humidity on mine explosions.[a] He has contributed a chapter in this bulletin on the use of steam and water sprays in Oklahoma mines (pp. 163–167).

In the Alabama mines of the Tennessee Coal, Iron, and Railroad Company sprays have recently been extensively introduced.

In the Shoenberger mine (see pp. 76–78) of the Pittsburgh-Westmoreland Coal Company, in Washington County, Pa., water sprays supplement exhaust steam. The principal intake enters the mine by the drift road or main haulageway. At night between 1 a. m. and 6 a. m. exhaust steam from three generator engines is allowed to enter with the intake air. It thoroughly saturates the air, and in the early morning the interior of the mine is said to be dripping with moisture. As the cloud of steam is very dense it is impossible to use it during the working hours. During this period a system of water sprays is used. The sprays are located about 1,500 feet from the drift mouth. There are 24 spray heads at intervals along a pipe about 450 feet in length. These sprays throw a strong, fine spray by direct water pressure. As they would drench men passing by, whenever an electric locomotive with a trip of cars is passing the sprays are turned down by manipulation of a valve in charge of a trapper boy.

Though an observation made by the writer on a cold day indicated that the air was saturated by the sprays, yet as the air had not yet attained the degree of warmth of the mine it is a question whether these sprays would have been sufficient but for the exhaust steam supplied at night at the main intake and continuously supplied in an independent split of air intaking at a back opening of the mine.

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[a] Effect of humidity on mine explosions: Trans. Am. Inst. Min. Eng., October, 1908.

HUMIDIFYING BY STEAM JETS.

The use of steam for humidifying was mentioned in the discussion on Sir F. Abel's paper, read in 1887.[a] Prof. Arnold Lupton said:

Perhaps one of the most ingenious ways was that of Mr. Stratton, in the Pochin pit, Tredegar collieries. He turned the exhaust steam of an engine into the downcast shaft and it had the effect of heating the air and damping it at the same time. It did very well in spring, summer, and autumn, but in winter it was not sufficient, because it would not heat the air enough, and therefore the steam was supplemented by water carts for laying the dust. This method of damping the air by steam was only applicable to mines of moderate depth, and consequently low temperature, say under 65° F., because it would make deeper mines too warm. The steam had done no harm to the roads or timber at the Pochin pit and it made the mine much pleasanter.

Apparently this system made no progress in England, as there are only casual remarks about it from time to time in current literature.

In the United States the plan of turning the exhaust steam from fan engines in winter into the downcast shaft has been considerably used in the western coal fields for many years, but the scheme has been mainly used in freezing weather to prevent ice from forming in the downcast shaft.

There does not appear to have been any systematic use of exhaust steam for humidifying ventilating currents until the last few years. Mr. Frank Haas, consulting engineer of the Fairmont Coal Company, has been an earnest advocate of this method of humidifying mine air to dampen coal dust and render it harmless. In an instructive paper[b] read before the West Virginia Mining Association, October 17, 1908, he proposes humidifying the mine air as an "efficient preventive. At about that time Mr. Haas installed a system of exhaust steam spray for humidifying the ventilating currents of the Monongah mines of the Fairmont Coal Company, and carried on a series of observations and tests during the following winter. The results of these important and successful experiments are presented by Mr. Haas as a part of this bulletin (pp. 150–165).

In a communication dated March 8, 1910, received from Mr. H. K. Knopf, general superintendent of the Pittsburgh-Westmoreland Coal Company, he states:

I wish to advise that in the fall of 1907 we installed a system of moistening the air at nearly all of our mines, especially at the shaft mines.

At our Acme mine at Bentleyville we now exhaust into the air shaft all steam from our fan engine, and during the severest weather we have always had live steam from the boilers from a 2-inch line. We find that we have at this mine from 98 to 100 per cent of saturation at all times. The steam at this mine carries back into the workings between 3,000 and 4,000 feet and in two years' time with the use of steam we have had no trouble with the roof; in fact, the roof, in my opinion, would hold up better with a

[a] Mining accidents and their prevention: Proc. Inst. Civil Engineers, London, vol. 91, 1887, pp. 91–92; republished in book form.

[b] Is dust, as such, explosive; and if so, what are the chemical reactions and the most efficient preventives? A pamphlet published by the West Virginia Mining Association.

uniform condition of moisture rather than when the moisture in the mine varies as it would do without having the moisture put into the air during dry, cold days.

At our Hazel Kirk No. 2 mine, which is also a shaft, we have steam from the fan engine and 1½-inch steam line from the boilers. At our Hazel Kirk No. 1 mine we have the exhaust from the fan engine and about 30 sprays, separated about 50 feet apart in the air way. During the daytime only a limited quantity of steam in addition to the moisture from the sprays goes into the mine, but at night a full amount of steam is turned in from the engine. At this mine we have obtained an average of 95 per cent moisture, and we have obtained 96 per cent of moisture even during the coldest days. At our Dunkirk mine we exhaust steam from the fan engine into the air shaft and we also have the exhaust from two or three pumps, in the mine, put into the air. All of the above-mentioned mines have force fans. At our Shoenberger mine we have the exhaust from three generator engines carried into the mine during the nighttime and we have a system of sprays during the daytime. At night, after the men have gone into the mine, the steam is turned on partially in addition to the sprays which work all the time. As soon as the fire bosses go into the mine in the morning, about 2 o'clock, a full head of steam is turned in, and shut off whenever they are ready to come out. In addition to the steam at the front part of the mine, we also have the exhaust from the fan engine to the back of the mine (on a separate split), together with the sprays which operate substantially at the front.

Observations were made by the writer at the Shoenberger mine on March 8, and except in one stretch of road about 3,000 feet from the mouth of the mine the road dust was uniformly dampened and plastic. The ribs and roof were free from dust and, though not dripping, were damp. The relative humidities of the ventilating currents are shown in the following table:

Hygrometric conditions of ventilating current at Shoenberger mine, Washington County, Pa., March 8, 1910.

Place of observation.	Dry bulb.	Wet bulb.	Relative humidity.	Condition of floor and ribs.
Main ventilating split:	°F.	°F.	Per cent.	
Intake air at entrance	33	31	80	
1,500 feet from entrance	41	40	92	Damp from night exhaust jets.
2,000 feet from entrance (inby water sprays).	43	42½	96	Very damp.
Last cross-cut main entry, 7,000 feet from entrance.	55	54	94	Floor damp, ribs and roof dampish, no dry dust.
Ventilating split at back of mine:				
Intake air at entrance	35½	31½	63	
600 feet from entrance and discharge of exhaust.	41½	41½	100	Air very foggy. Walls and ribs dripping, floor wet.
Near inby end of split	53	52	94	Floor very damp, ribs and roof dampish.
Another split	53¾	53	95	Do.

It would appear from the readings in the main ventilating split that the water sprays used near the main entrance were not sufficient to humidify the mine at the observed temperature and humidity of the entering air—that it was the large steam exhaust at night that supplied the chief quantity of water, the water sprays giving some moisture during the day.

The exhaust steam used in the independent back split of air shows the efficiency of this method where it can be applied. The exhaust steam in the main entrance was not used during the day because the fog produced was so dense that it would not have been possible to use the road for haulage—the main intake coming in on that road.

QUICK-FLAMING EXPLOSIVES.

The report of the Prussian fire-damp commission in 1885 stimulated the research in Germany for the development of explosives which would not ignite fire damp and coal dust under ordinary conditions. Sir F. Abel in his paper on mining accidents and their prevention in 1887, expressed the belief that the explosives then being introduced in Germany, robuite, securite, and carbonite (in its original form), were not flameless, and he did not consider them promising means. He advocated inclosing the explosive in water cartridges and similar devices. Nevertheless, the improvement and development of the so-called nonflaming explosives proceeded so actively in Germany that by 1890 they began to be regarded as the proper explosives to be used in coal mines.

The report of the British royal commission in 1894 in mentioning "flameless explosions" says (p. 25):

> Many different patent explosives have been brought to the notice of the commission. The so-called "flameless explosives" are largely in use in all parts of the country and as the result of practical experience are generally pronounced to be effective substitutes for gunpowder, and certainly very much safer. Each of these compositions has its advocates and each is said to be flameless or practically so. As far as dust is concerned, the current opinion appears to be that they are perfectly safe, but there is considerable doubt as to how far the small flash or scintillation, which many witnesses say they display, renders them dangerous in the presence of gas.

By 1896 the agitation for better mine explosives caused the passage of a coal-mine regulation act in England, under which authority was given to prohibit the use of dangerous explosives, and an explosives testing station was established at Woolwich in 1897. Since that time all explosives used in gaseous or dusty mines must pass the tests at the Woolwich station. Those that pass are placed on the list of "permitted explosives."

In Germany a station for the testing of mine explosives in the presence of gas and dust mixtures had already been opened in 1894 at Gelsenkirchen, Westphalia, under the direction of a government engineer. The German mining department does not allow the use of long-flame explosives in coal mines.

A station similar to the German one was established by the Belgian Government at Frameries in 1902. The Belgian mining department publishes lists of explosives which have passed the required tests.

Austria has a station at Mährisch-Ostrau in which explosives are tested by discharge in the open gallery, not from a cannon. This Government also has a "permitted" list of explosives.

France does not maintain an official testing station, but the mining regulations require that an explosive for use in coal mines shall not develop sufficient heat to ignite fire damp, as determined by calculation of the chemical reactions taking place at the moment of explosion.

It has thus become a requirement in the coal-mining countries of Europe to employ only such explosives as have passed certain tests, or have met certain requirements. It is fully recognized that no explosive has yet been produced that is absolutely free from flame, but when the explosive used in a shot does not exceed the amount specified as allowable, it has so little flame that gas and dust under ordinary conditions will not ignite from its discharge. The quantity that may be used of each explosive is therefore specified. It has been termed the "charge limit" by M. Watteyne, head of the mining department of Belgium, and this term has been generally adopted.

In the United States, so-called "safety" blasting powders were not introduced into the bituminous coal fields until about two years ago, although certain nonflaming explosives had been used earlier in special instances in some gassy mines of the anthracite region. There was no extensive use of such explosives until the present year (1909); in fact, some of the earlier explosives had been withdrawn from the market by the manufacturers.

Soon after the Pittsburg station was established and tried out informally, a letter was sent by the Director of the United States Geological Survey, on January 9, 1909, to the manufacturers of explosives in the United States setting forth the conditions under which explosives would be examined and the nature of the tests to which they would be subjected. By May 15, 1909, 29 explosives had been tested. Of these 17 passed the test requirements and were termed "permissible explosives." A circular was issued to this effect on May 15. By October 1, 1909, 14 additional explosives had passed the requirements and a second circular was issued reporting this fact. A third circular, issued May 16, 1910, listed 14 additional explosives, or 45 in all.

Although, as it is made clear in the circulars, no explosive is absolutely safe under all conditions, there is, nevertheless, very little chance of causing an explosion of fire damp or coal dust with one of these permissible explosives under any ordinary conditions, provided it is used in accordance with the conditions set forth in the circular.

The contrast between the "permissibles" and black powder is very strong. With equivalent quantities the flame of black powder is more than three times as long and has a duration from 2,500 to 3,500 times that of a "permissible explosive."

By the use of "permissible explosives" the number of disasters developing from blown-out or overcharged shots is reduced to a minimum. As a majority of the great mine disasters in this country have been caused by blown-out or overcharged shots of black powder, the general adoption of the "permissible explosives" should result in a tremendous reduction in the number of such disasters. There are, however, other initiating causes of great explosions, for instance, the ignition of any small body of fire damp. Under some conditions an electric arc may cause an ignition of coal dust. While no large-scale tests of the explosibility of coal dust by electric arc or hot wire have been made at the Pittsburg station, the possibility of such ignition is shown by the laboratory experiments conducted by Messrs. Bedson and Widdas in England, already referred to, and by the preliminary laboratory experiments of Dr. J. C. W. Frazer, an account of which he gives as part of this bulletin (pp. 99-133).

ROCK DUST.

The British accident in mines commission in 1886 said:

> The observation recently made in Germany, in some preliminary experiments, that a thin layer of fine angular sand strewn over mine dust appeared to have the effect of preventing the communication of flame from a blown-out shot to all but the most inflammable dusts is worthy of a passing notice.

Messrs. W. N. and J. B. Atkinson [a] suggest, among other remedial measures, that "bottom dust might be rendered uninflammable by an adulterant like sand."

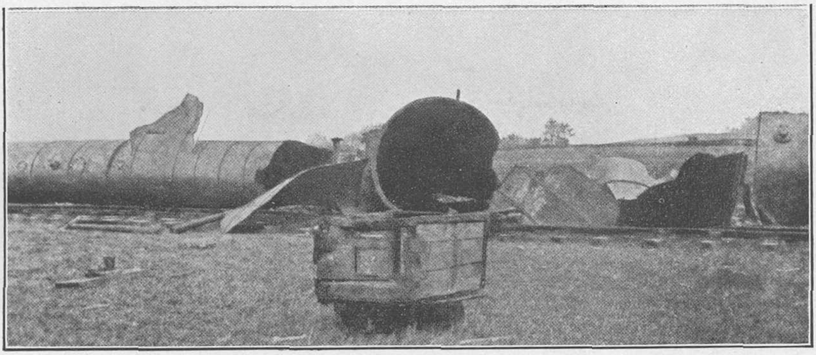
Mr. W. E. Garforth in giving testimony before the royal commission in 1891, in reply to a question about the Altofts explosion which took place October 2, 1886, said: [b]

> Those roads containing coal dust were affected, those containing dirt dust or only a sprinkling of coal dust were not affected. * * * I think you should conduct some experiments on the different kinds of coal dust and dirt dust. I believe dirt dust will really be the means of preventing an explosion on some roads. More so than water.

The proposal to use stone dust to neutralize coal dust did not attract public attention until the Mining Association of Great Britain established their experimental gallery at Altofts under the direction of Mr. Garforth. The first experiments, beginning May 12, 1908, were to standardize the apparatus, and to educate the mining public in the explosibility of coal dust. The great size of the gallery (see p. 21) and the heavy explosions of coal dust that were produced attracted wide attention.

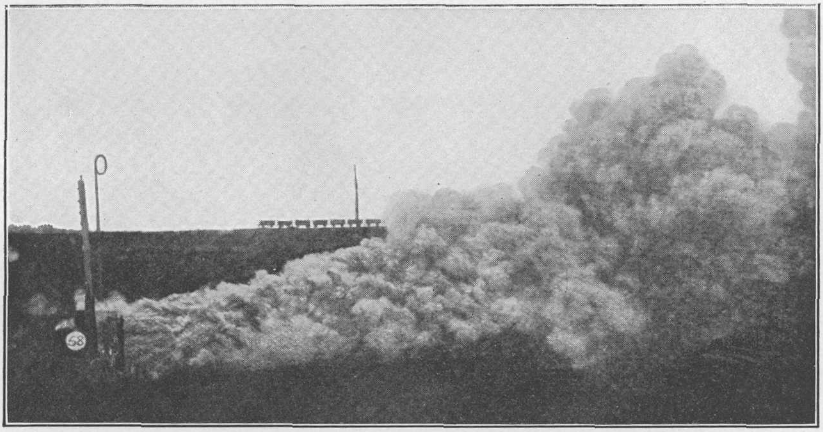
[a] Explosions in coal mines, p. 127.

[b] First Rept. Roy. Comm., 1891, p. 125.



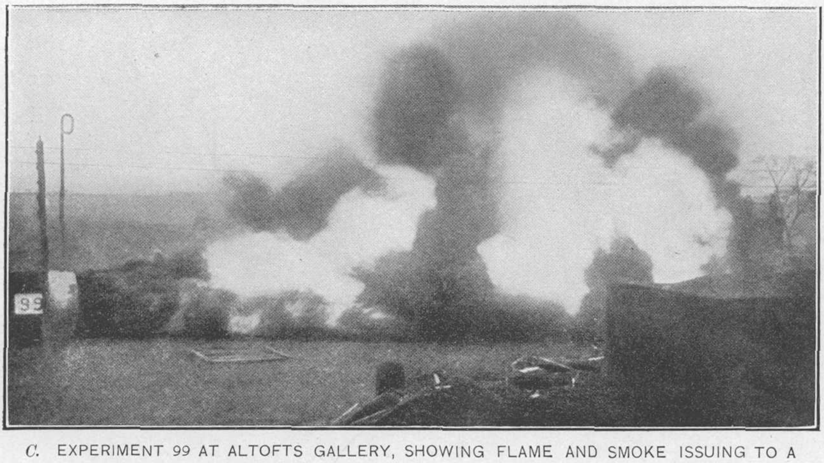
A. ALTOFTS EXPERIMENTAL GALLERY AFTER EXPLOSION OF DUST OCCUPYING 450 LINEAR FEET OF GALLERY, AUGUST 11, 1908.

The vibration of the explosion was felt at a distance of 7 miles. (From Colliery Guardian.)



B. EXPERIMENT 58 AT ALTOFTS GALLERY, SHOWING STONE DUST AND SMOKE ISSUING FROM GALLERY AS THE RESULT OF AN EXPLOSION OF THE 275-FOOT COAL-DUST ZONE.

The flame penetrated only 54 feet into a stone-dust zone of 100 feet, therefore not igniting another zone of coal dust at the outer end of the gallery. (From Colliery Guardian.)



C. EXPERIMENT 99 AT ALTOFTS GALLERY, SHOWING FLAME AND SMOKE ISSUING TO A DISTANCE OF 160 FEET FROM EXPLOSION OF 375 FEET OF COAL-DUST ZONE.

Flame shows white in the view. (From Colliery Guardian.)

On June 13 an experiment (test 13) was made with a stone-dust zone, 158 feet long, placed on the return side of the coal-dust charge, 369 feet long. On the intake side there was a 175-foot dustless zone. The flame traveled 44 feet only over the stone dust, but 110 feet on the dustless zone, and at this point the force was so great that it burst two of the boiler plates, of which the gallery was built, the flame finding relief upward.

Test 24, August 8, 1908, showed a penetration of flame into the dirt dust (ground shale) of only 155 feet, while on the opposite (return) side the explosion was very violent.

In test 25, August 11, 1908, a heavier loading of coal dust than that previously used was tried, 450 pounds over 450 feet of gallery. The explosion was notable for its violence, the result being thus described:[a]

> Three boilers forming the downcast were wrecked. [See Pl. VI, *A*.] Several pieces of boiler plate were blown high into the air a considerable height and distance. The flame shot out to great length from the downcast and the vibration of the explosion was felt more than 7 miles away.

In 29 experiments without interposition of a stone-dust zone, flames projected from the gallery averaged 156 feet in length.

Experiments with stone dust continued and in September a length of coal dust (367 feet) was laid between two stone-dust zones of 210 feet each, which effectually extinguished the flame in each direction. This experiment was witnessed by a number of the royal commission on mines.[b]

The gallery was closed for the winter in November, resuming experiments in June. While no conclusions have been reached, the results of experiments that have been made public indicate that with a charge of 375 pounds of coal dust distributed over 375 feet the flame of the coal-dust explosion will be extinguished by the stone dust after penetrating 50 to 125 feet into it, the distance depending on the method of application. The most effectual method tried was to place stone dust on noninflammable brattice cloth on the tops of timbers. When the explosions knocked these out the stone dust fell in a shower on the flame. Photographs taken after typical explosions are reproduced in Plate VI, *B* and *C*.

The pressure developed by one of the coal dust explosions was 113 pounds per square inch at a point 375 feet from the initiating point of explosion. The published account says:[c]

> The speed of travel of pressure, not necessarily the speed of travel of the flame * * * has shown the average speed, from the time of ignition to a point 275 feet distant, to be about 1,400 feet per second.

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[a] Colliery Guardian, August 28, 1908, p. 411.
[b] Idem, July 30, 1909, p. 221.
[c] Idem, July 30, 1909, p. 219.

The application of stone dust to mine passageways is now being tried by Mr. Garforth in the Altofts colliery. The method adopted is to divide off sections of the mines by stone-dust zones of 600 feet in length. The roof material is ground fine and applied dry. Plate VII shows part of the wall in its natural condition, the other part treated with stone dust. The Altofts management state that stone dust by reason of its greater density displaces the coal dust on ledges, and as the angle of repose of the stone dust is greater it falls to the ground and is covered up by additional stone dust. The stone dust must be renewed at intervals depending on the rapidity with which coal dust gathers.[a]

The formal report of the committee in charge of the Altofts experiments to the royal commission will be awaited with great interest.

BRICK OR CONCRETE LININGS AND WET ZONES.

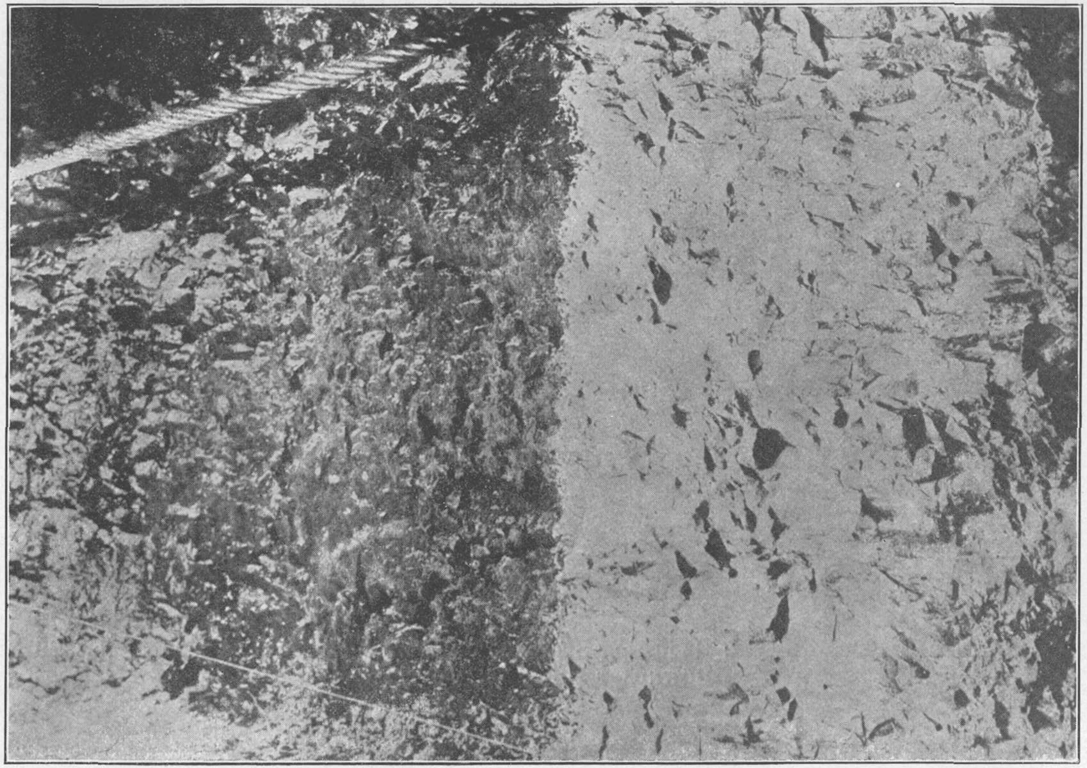
Lining sections of entries at regular intervals in a mine to limit the extent of an explosion has received some attention abroad. The ideal system is to line the passageways throughout with brick or concrete, and this has been done systematically in a new mine of the Bethune Company in the Pas de Calais district. In September, 1908 (when it was visited by the writer), 3,500 meters (11,000 feet) of reenforced concrete lining had been constructed, so that a visitor entering the mine passed through a concrete tunnel, electrically lighted up to within a few hundred yards of the face. The linings are smooth and are easily kept clean and free from dust, so that it would appear impossible for an explosion originating at the face to penetrate any considerable distance through the gangways.

The cost of such linings is considerable, yet in a mine where the roof is poor, requiring much timbering, and the mine is to be long-lived, the saving effected in the maintenance of the roadways will probably pay in a few years for the additional cost of the lining. The managers of the Bethune mines state that the underground maintenance cost in the mine mentioned is only one-fifth of the average maintenance of their other mines in the same district.

The method of lining generally used has been to divide the mine up into sections and to make the length of lining sufficient to prevent a flame of an explosion in one section from passing through to another section—in other words, to create a "dustless zone." Until the Altofts experiments were begun there was very little definite idea as to what length a dustless zone should have. In earlier discussions lengths from 100 to 200 yards had been suggested.

For prevention of dust explosions the importance of lining the passageways is not due to the lining as such, but to the ease of cleaning

[a] Colliery Guardian, October 1, 1909, p. 676.



SIDE OF ROADWAY IN ALTOFTS MINE, SHOWING METHOD OF APPLYING STONE DUST AS A PREVENTIVE OF EXPLOSIONS.

Natural wall at left; wall treated with stone dust at right. (From Colliery Guardian.)

and to the fact that it allows the free use of water without weakening the roof, or the floor where there is an inverted arch as well.

Except at the Bethune mine mentioned above it has rarely, if ever, been contemplated to completely line the passageways; the usual thought has been to employ linings to divide the mine into sections. In order to decrease the necessary length of dustless lining, water curtains have been suggested and have been experimented with to some extent in the gallery at Rossitz, in Austria. In experiments there with water curtains the usual flame length of dry dust without the curtains (147 meters) was shortened about 30 meters (97 feet), but the flame still penetrated a wet zone about 21 meters (68 feet). The conclusion was that a wet zone alone must be at least 60 meters (195 feet) long, but that apparently a zone supplemented by water curtains at either end could be shorter. These figures are somewhat below those indicated by the Altofts and Liévin experiments, where larger initial explosions were tried.

The question how long lining zones should be that are kept clean and free from coal dust can better be determined after the present series of tests at the Altofts and Liévin stations have been concluded.

TENTATIVE CONCLUSIONS ON THE DUST PROBLEM.[a]

FACTORS AFFECTING EXPLOSIBILITY.

VOLATILE COMBUSTIBLE MATTER.

That coal dust will explode under some circumstances, both in the presence of fire damp and without it, is now generally accepted by mining men. The writer fully agrees with this and takes the following views of the explosibility of dust and the conditions necessary for explosion.

Experiments at Pittsburg indicate that under ordinary conditions the dust must be from coal having at least about 10 per cent of volatile combustible matter, though in certain foreign experiments it is claimed that explosions were obtained with charcoal dust.

Dusts with higher percentages of volatile combustible matter are more sensitive, ash, moisture contents, and size being constant. This view is based partly on the preliminary experiments at Pittsburg and on the results of experiments of M. Taffanel and other foreign investigators.

STRUCTURE AND SIZE.

Physical structure and size of the dust particles are factors in the relative sensitiveness. In coals approaching the border line of non-explosibility, structure and particularly size are the more important,

[a] It must be understood that the conclusions here stated are those of the writer and are of a tentative character, subject to revision as further investigation is carried on at the Pittsburg testing station and elsewhere.

and affect ignition. That is, the less readily the dust gives up its gases the larger and more intense must be the igniting flame.

Whether or not concussion or compression of the air at the moment of attack by the flame is required for the ignition of the less sensitive dusts and the propagation of the flame is a question yet to be answered, but it is self-evident that the larger and heavier the particles are the more difficult it is for the air waves in advance of an explosion to bring them into suspension where the flame can strike them.

DENSITY.

For continued propagation of flame the dust particles must be so close together that the burning gas enveloping one dust particle will cause distillation of the volatile matter of the next particle and ignite it. In other words, at each successive moment of inflammation there must be a certain density of dust for each character and size of dust.

It appears to the writer that the combustion of the fixed carbon of an average-size particle of coal dust will not take place until the volatile matter of the particle has been volatilized and burned in the surrounding air. If this is true, the oxidation of the fixed carbon probably does not, except in dust particles of minutest size and greatest purity, take place in time to assist in the first extension of the flame, although it is undoubtedly an important factor in the succeeding moment, intensifying the flame, and hence increasing the violence and pressure of the explosive wave.

The analyses of burned dust from explosions, both in mines and in the Pittsburg gallery, show an increase in percentage of ash over the ash content of the original coal often considerably greater than the increase due to expelling the volatile matter. Such an increase shows that there has been combustion of the fixed carbon. The increase in ash has been especially marked in the 200-mesh dust used in the Pittsburg density tests. (See p. 37.)

M. Taffanel's experiments with anthracite and those at the Pittsburg station indicate that under the conditions in the galleries used anthracite dust will not propagate an explosion. This supports the view expressed above that it is the burning volatile combustible gases that carry forward the initiating flame and that the combustion of the fixed carbon is secondary.

MOISTURE.

Moisture contained or carried in coal dust is probably converted to steam before gas is evolved from the dust particles, and if enough moisture is present the absorption of heat in this way may prevent sufficient heat from being imparted to adjacent dust particles to evolve and raise their volatile gases to the ignition point. Furthermore, if the moisture in or surrounding each particle of dust is sufficient in quantity, the vapor therefrom will dilute the evolving gases or else tend to surround them with an outer incombustible envelope and so prevent the immediate ignition of the combustible matter necessary for propagation.

ASH CONTENT.

The ash content of the coal, within ordinary limits, does not appear to affect the explosibility of the coal dust; but if an inert dust, such as stone dust, is raised into the atmosphere with the coal dust by the advance air wave, it will affect results in two ways—by separating the coal-dust particles with a barrier and by absorbing some of the heat of the impinging flame, and thus lowering the temperature below that necessary for the ignition of the gas distilled from the adjacent coal-dust particles.

OUTWARD CONDITIONS.

The writer concludes that the outward circumstances under which coal dust will explode may be summed up as follows: Sufficient dust must be brought into suspension by a preliminary shock or concussion producing a violent air wave; or else the dust must be so minute that it is already suspended in a dense enough cloud at the moment when the flame impinges. The latter effect is produced only under some peculiar circumstances by which a large amount of fine coal dust is thrown into a strong air current and carried to the igniting flame. The former effect may be produced by a heavy shock like that from a falling body, but is much more likely to result from a preliminary explosion of fire damp or, more commonly, of an explosive.

CONDITIONS AFFECTING PROPAGATION OF EXPLOSIONS.

AMOUNT OF DUST.

The weight of coal dust that must be thrown into suspension to permit propagation of an explosion depends on (*a*) the percentage of volatile combustible constituents; (*b*) the amount of contained and adhering moisture; (*c*) the presence of foreign substances like stone dust; and (*d*) the size of the dust particles, the effect of which is two-fold—the smaller the particles the more easily the air concussion can raise them, and the more surface is exposed for the evolution of gas.

The minimum density of the dust cloud necessary to propagate an explosion evidently varies with the initial cause as well as with the character of the dust. Using 190-mesh bituminous dust, M. Taffanel obtained explosions regularly with a density of 70 grams per cubic meter (0.07 ounce per cubic foot), and in one instance obtained propagation with as low a density as 23 grams per cubic meter (0.023 ounce per cubic foot). In the experiments at the Pittsburg station with 200-mesh dust from the Pittsburg coal seam, in a much larger gallery, but also with far larger charges of explosive, two propagations were obtained with as low a dust density as 32 grams per cubic meter (0.032 ounce per cubic foot).

Density tests with the coarser sizes have not yet been tried in the Pittsburg station.

MOISTURE IN DUST AND IN AIR.

The experiments with wetted dust at the Pittsburg station have been very instructive. The first attempt has been made to define the amount of water that must be present with the dust to prevent propagation. It is true that these experiments were few and were made with dust from the Pittsburg seam only, which is possibly more sensitive than the average bituminous dust. On the other hand, the igniting charge was only 2½ pounds of black powder. In the interior coal fields it is not at all uncommon for charges of 5 to 6 pounds or more to be used and for blown-out shots to occur with such charges. Hence, despite the possibly less sensitive character of the coal dust in these fields, the initiating cause of explosions may be greater, and it would not be safe to assume that a less percentage of moisture than that indicated by these preliminary experiments would render the coal dust inert.

Where there is a large amount of dry coal dust, judging from the Pittsburg experiments, a humid atmosphere has little effect on ignition of dust or propagation of an explosion. A long continuance of the humid conditions renders the coal dust moist and inert, but the presence of moisture in the air at the moment of explosion is not sufficient to prevent an explosion; that is, not enough moisture is carried by the mine air to reduce materially the temperature of the flame. Fully saturated vapor at 65° F., an ordinary mine temperature in this country, weighs 6.78 grains per cubic foot (15.5 grams per cubic meter). Coal dust suspended in such a saturated atmosphere in a cloud of moderate density weighs, say, 200 grams per cubic meter. At the figures given the weight of vapor is but 7.8 per cent of the weight of dust. The Pittsburg experiments with wetted dust showed that several times this percentage of moisture in the dust, in addition to a nearly saturated atmosphere, was required to prevent propagation.

Probably with a low dust density the relative humidity of the air would be an important factor in tending to prevent the initiation of an explosion. However, *the great purpose of artificially humidifying mine air is that it may serve as a vehicle for carrying water to the dust.*

MIXTURE WITH INERT SUBSTANCES.

When the dust is abundant, the effect of high ash content, unless that content is excessive, is apparently not noticeable. The upper limit has not yet been closely defined by experiment. The effect of intimately mixing coal dust with shale dust or stone dust has also not been fully determined experimentally. The few tests in this direction conducted at the Pittsburg station have been with "road dusts" or other coarse mixtures, and the tests with these indicate that the amount of the inert substance has to be very large, possibly equal to the amount of pure coal dust. The tests with finely pulverized stone dust in the Altofts experiments have been directed to supplanting or covering up coal dust in certain zones, but not to mixing stone dust with the coal dust.

ADVANTAGES AND DISADVANTAGES OF PROPOSED REMEDIES.

In reviewing the methods for preventing coal dust explosions or limiting them to certain zones the writer presents merely his own views and conclusions, subject to change as the investigations proceed. The remedial measures will be taken up in order as already given (pp. 66–83). The writer believes that all have more or less merit, except the water boxes or sprinkling cars of primitive type.

FORCE SPRINKLERS IN CARS.

Water cars with force sprinklers, in which the pressure is produced by pump or air pressure, if used frequently and thoroughly, are good. The great danger is that they will not be so used throughout all the mine, owing to their interference with the haulage of coal, and frequently owing to the lack of tracks in the air course or manways. When used intermittently the water-car system is useless because the dust is not wetted; as the drops of water do not mix with it, they are exposed to the air currents and quickly dry up.

CHEMICALS.

The use of calcium chloride and similar salts has not yet been sufficiently tested to permit a conclusion as to its effectiveness in preventing explosions. If it renders the dust merely dampish—that is, not sufficiently moist to prevent explosions—it may improve the sanitary condition and lessen the quantity of float dust. It may also prove to be effective in supplementing intermittent sprinkling, enabling the dust to absorb drops of water that would otherwise be taken up by the air current.

CLEANING UP DUST—WASHING DOWN WALLS.

Cleaning up coal dust and sending it out of the mine is a plan used more or less under all systems, but applied only to large masses of dust. The plan can not reduce the quantity below the danger point.

Thorough washing down of roof and walls with hose is required by the mining laws in Germany, and in this country in Utah. If thoroughly and frequently done, it is undoubtedly most effective. The difficulty is that usually it is not done systematically and thoroughly. It is a system that can not be effectively applied to shaly or weak roofs without resulting in many falls and great cost of timbering.

PERMANENT SPRINKLERS—ZONAL LININGS.

Using permanently located sprinklers, attached to pipe lines and running continuously, but with a flow that can be varied according to need, is very effective in saturating the mine air within a moderate distance of each sprinkler, and through this means gradually wetting the dust. One of the great merits of the system is that the sprinklers can be distributed where most needed; that is, where there is a tendency to produce the most dust or where the humidity of the air currents is lower than it should be. A disadvantage in some mines is that the moisture causes falls of roof. Some of the evidence of this fact is derived from trials of intermittent rather than continuous wetting. Nevertheless, where there is roof material that will come down, or fire-clay floor that will swell immediately on contact with water, in order to use sprinklers it may be necessary to introduce brick or arched linings, sometimes with concrete floor and sump, and to place individual sprinklers in the lined sections. The linings would serve two purposes—to catch any condensed water from the sprays and to provide a damp and dust-free zone, limiting a possible dust explosion from either side.

The use of more complete zonal linings is well worthy of consideration for long-lived mines or long-lived entries (particularly the main entries), not alone as a dust remedy, but also for fire protection.

USE OF EXHAUST STEAM SPRAYS.

Sprays.—Humidifying the intake air current with exhaust steam sprays is much the easiest and cheapest method of introducing moisture into a mine where the ventilating fan is run by a steam engine.

Supplementing fan steam.—The quantity of steam that it is necessary to use in the fan engine for ordinary air-ventilating pressures is sufficient to humidify the air in moderately cold weather, but in extreme cold weather is insufficient. Therefore it must be supplemented by live steam or, as suggested by Mr. Frank Haas, in order to insure that it is used, by passing more steam through the engine.

The same result could be accomplished by passing the steam through a registering meter.

Disadvantages.—The disadvantage of steam sprays is that the steam fogs the air current in cold weather, so that the sprays can not be placed on the haulage roads without considerable discomfort and danger of collision. It therefore seems requisite to employ a blowing system of ventilation, placing the steam sprays on the air way at the intake and throwing the return air on the main haulage road. This is manifestly unsafe to do in gassy mines or in mines liable to an outburst of gas, particularly if the method of haulage is electrical. The only alternative in such a mine is to have an additional entry for the return air way, making the ventilation in the haulage way "neutral" or passing through it a very small but sufficient supply of fresh air. In most old mines this is an impossible condition; therefore the decision as to the use of the steam-spray system must depend on whether the mine makes sufficient gas to prevent the return air being passed through the haulage way. In much the greater number of mines, particularly in the Middle West, there is not sufficient gas to prevent this being done; therefore in such mines the use of steam sprays appears to be one of the best systems where the roof conditions permit it. A compromise method is that used at the Schoenberger mine, described on pages 76–78, in which the steam sprays are used in the haulage road at night only, water sprays being used on the day shift when coal is being hauled.

Danger to roof.—It has been held by many mining men that the use of exhaust steam for humidifying would be especially severe on the roof. In the opinion of the writer this is not generally true. The condition of humidity obtained by its use is very uniform. Where humidifying is not done it is the alternate drying out and wetting due to the changes in weather that causes most of the trouble. The roof is not subjected to any more severe conditions by steam or water sprays than in spring when hot moist air enters the mine. Later in the summer during the hot weather the same high degree of moisture prevails, but the roof, becoming acclimated, as it were, to this condition, is not as likely to fall as during the spring, when the change of temperature and humidity took place. If, when cold weather comes, the humid condition of summer is maintained by introducing sprays, the roof will not be subject to violent changes in humidity.

Heating intake air.—The plan of merely heating the incoming or intake air to produce summer temperature without introducing additional moisture has sometimes been proposed as a remedy. The fallacy of the argument will be obvious to one familiar with the principles of relative humidity and their application to mine air.

Heating the intake air as an aid to quick humidifying, where either steam or water sprays are used, has been tried more or less, with some diversity of opinion as to results. Mr. Frank Haas's experiments with heating the intake at the Monongah mine, as described by him on pages 158–161, indicate that there is no need of such heating. The walls of the passageways effectively heat the air in cold weather, so that the expense of artificially heating a large volume of air does not appear necessary, if the intake is kept humidified to the point of saturation as the temperature rises. Some mine operators have considered heating of great advantage.

In the use of steam sprays the steam raises the temperature of the incoming air to some extent, depending on the relative temperatures of the steam and air as well as on their relative weights for equal volumes. The lower the temperature of the external air the greater the weight of steam necessary to be introduced; hence the greater the temperature rise of the incoming air. Practically, this rise will range from 8° to 15° F., depending on a variety of conditions. Theoretically, if we should disregard the conductivity of the walls of the passageway and assume that all the steam in excess of that immediately required for saturating the incoming air is condensed, the rise would be very much greater. There are so many variable factors and the influence of the walls is so great that it is impossible to determine the rise by calculation.

Vaporization.—If the steam sprays are placed at the entrance of the intake of the mine, when the external air is considerably colder than the normal temperature of the mine, the difference being greater than the rise resulting from the heating by the steam sprays, the steam in excess of the vapor capacity condenses, and some water falls to the ground, but as the air current moves rapidly most of it is carried along mechanically in the form of fog. As the air current travels along the mine passage and absorbs the natural heat from the walls, its vapor capacity increases and the fog is gradually revaporized, thus keeping up saturation until there is total disappearance of the fog or visible moisture. If at this point the heat of the air current has reached that of the strata or walls, the air will remain practically saturated throughout the mine, but if the temperature still rises the air current no longer remains saturated, but has a relative humidity that decreases as the temperature rises.

Cooling effect of vaporization.—When steam or water sprays are used, the vaporization of water or the revaporization of fog absorbs heat with the result of lowering or keeping down the temperature of the air. This result is only temporary, as the passage walls impart the difference in heat in a relatively short time. The amount of the temporary reduction or retardation of temperature under mine conditions is practically impossible to calculate on theoretical grounds, owing to the undetermined heating effect of the passage walls. Water sprays can not well be employed until the air has risen in temperature to about 32° F. The point in the mine at which this takes place when no artificial heating is done necessarily varies with the temperature of the incoming air. The sprays must therefore be arranged at intervals and turned on or off according to the temperature. The important point is to keep the air saturated as it rises in temperature. By either method of humidifying steam or water sprays, with careful attention there is no serious difficulty in keeping the dust moist and in a relatively safe condition.

Effect of humid air on health.—In England, where the mine temperatures are 15° to 20° F. higher than in the mines of this country, owing to the greater depth, fear is expressed frequently by the mining men that a humid condition of the air is unhealthy and enervating. The spreading of the intestinal disease called ankylostomiasis, which at one time afflicted large numbers of the German miners, was by some ascribed to the warm humid air of the German mines. Be that as it may, sanitary precautions have now largely stamped out the disease. Hard physical labor may be done in a saturated atmosphere at 60° to 65° F. with much less discomfort than at 75° to 85°, aside from that due to the greater heat, because the warmer air carries twice the weight of water per cubic foot. Hence conditions in this respect are very different in England and Germany from those in this country. The writer has observed no discomfort in a saturated or nearly saturated atmosphere at 65° F. The air of most mines in summer is in this condition. Only when the air is supersaturated or foggy does it become unpleasant.

STONE DUST.

The use of stone dust is the most recent suggestion for either preventing or limiting explosions of coal dust. As the method is only in the experimental state, it is too early to express any decided opinion. The results at Altofts appear very favorable. Not all the mines in this country provide a suitable stone for grinding, but burned dirt piles or clay or sand are nearly always available, and to a limited extent thoroughly burned ashes from the boiler plant.

The method is not so adaptable to room and pillar workings as to the long-wall system, but it may prove a valuable alternative remedy for coal dust where the humidifying methods are considered inapplicable on account of danger to the roof, or in those mines in the arid parts of America where water for humidifying is not available.

If in addition to wetting coal dust throughout a mine by one of the foregoing methods "permissible" explosives are used for shooting coal at the face, or for brushing or grading the roadways, the chances of starting a wide-sweeping mine explosion are reduced to a minimum. As a means of prevention of dust explosions, the writer would place the employment of permissibles at the head.

OBSERVATIONS ON MANIFESTATIONS OF COKED COAL DUST IN MINE EXPLOSIONS.

CHARACTER OF COKED DUST.

The mining engineers of the Survey have made investigations of all the explosions of any moment that have occurred since July 1, 1908.

Of those which have been personally investigated by the writer, and in which dust played the most important part (though not necessarily at the origin), the most serious were those at Marianna, Pa., November 28, 1908, in which 156 men were lost; at the Franklin slope, Johnstown, Pa., October 31, 1909, in which 13 men were killed and 2 others seriously burned; at Primero, Colo., January 31, 1910, in which 75 men were killed; at Mulga, Ala., April 20, 1910, in which 35 men were killed; and at Palos, Ala., May 6, 1910, in which 84 men were killed.

In these explosions the coke manifestations were strong and very characteristic. From a study of these and previous explosions investigated by the writer, there appear to be five phases of coke developed in a mine explosion:

1. Bright splashes of coke on the open exposures, adhering to the ribs and to a less extent to the roof, indicating an abundance of dust and an intense heat, but not much movement. Such coke was found near the heads of entries.

2. Less friable coke or caked dust, in some places over an inch thick, sometimes found on the exposed surfaces of the walls and posts of rooms and to a lesser extent on entries facing the source of explosion. Such coke is found near the origin of explosions or where there have been secondary explosions. It indicates an abundance of dust and not much movement.

3. Individual particles of coke, generally bright, and in some places close enough together to form a thin scale. This is sometimes found driven into crevices facing the approaching explosive blast, but usually is on the reverse side of timbers, projections, or rib corners. Such coke indicates a violent sweep of the explosive blast too strong to allow deposition on facing exposures, but which whips around the projections and deposits the semiplastic coke on the lee side.

4. Minute globules of coke as large as $\frac{1}{16}$ inch diameter and smaller. Many of these are perfectly round, and on the interior nearly hollow, with one or more cells. They are to be found on top of cars at the face of entries or on other surfaces on which they can be seen. Those globules falling to the floor are difficult to observe. Such spheres of coke are like tiny balloons. They do not adhere together, but have evidently been cooled in transit through the atmosphere. Their occurrence, so far as observed, is only as the result of explosions in mines in which the coal is of a distinctly coking nature or in which the bitumen is considerable, as coal of the Pittsburg seam. It would seem that these glowing float globules, or other particles, might be

important in carrying an explosion into remote corners after the active flame of an explosive wave has temporarily died away. Then should any gas be present it would be greatly compressed, so that when the red-hot particles penetrated the compressed gas at the head of an entry or other closed place they would cause its ignition, and thus a secondary explosion would be set up.

5. The fifth kind of coke is not a coke from dust. It is formed where the flame of the explosion has lingered and the flame or adhering coked dust has ignited the coal ribs, sufficient oxygen being present for the combustion to go on. This sometimes occurs in a room, and such a place, if a large amount of coke has been present, has frequently been mistakenly considered the point of greatest intensity of the explosion.

In no place has it come to the observation of the writer that coking of the face or ribs has been due to the direct explosive blast; this would appear to be an after-effect. Generally coked dust has been caked while in the air, and in the plastic or semiplastic state has been thrown against exposed surfaces. Coke from dust is more likely to be found upon the timbers and coal ribs than upon the roof or rock ribs where such are exposed; but this is by no means invariably so. However, there does appear to be a selective action. It was peculiarly noticeable in a certain entry in the Franklin Slope mine, in which several slate partings with a smooth fracture showed along the ribs; the coke adhered conspicuously to the coal above and below each of the partings, but not to the partings themselves.

The coke or caked coal found after explosions shows a marked increase in ash and decrease in volatile matter as compared with the average coal of the mine. Even when no coking is apparent to the eye there may be a considerable loss of volatile matter in the dust. This is indicated by a comparison of dust gathered near the shaft bottom at Marianna with the standard coal of the mine, as shown in the following tabulation:

Proximate analyses of dust and of coal from Marianna mine.

	Standard coal. [a]	Dust heated in the explosion.
As collected:		
Moisture	1.86	[b] 3.99
Volatile matter	33.14	19.56
Fixed carbon	59.00	45.67
Ash	6.00	30.78
	100.00	100.00
Moisture and ash free:		
Volatile matter	35.97	29.98
Fixed carbon	64.03	70.02
	100.00	100.00

[a] Sample of coal full section of seam, as mined.
[b] Moisture undoubtedly absorbed after explosion; sample was gathered about ten days after it.

Where there is actual coking the loss of volatile matter and increase in ash is more noticeable. The high percentage of ash shown in the above dust analysis is presumably due to inclusion of foreign matter and not to complete combustion, although that may have played some part.

POSITION OF COKED DUST AFTER AN EXPLOSION.

The observation of the writer has been that at the originating point of a coal-dust explosion, and near by, the coked particles are projected directly upon the exposed surfaces of props, caps, collars, and walls, particularly upon the upper portions toward the roof. In other words, the coked dust faces the originating point.

As found in mines in which the coal cokes strongly, the coked dust near the source of explosion is usually in thick loosely cohering masses, and where the dust is abundant this coke scale may be as much as half an inch or even an inch thick. The coking or rather caking through an individual scale is uniform, but the coking process has been carried only so far as to render the individual grains plastic enough to cohere and to lightly stick to surfaces. A slight touch will detach and break up the scale. Such coke is dull in luster and presents a rough granular appearance. It often contains foreign matter, pieces of slate, or fragments of timber.

A few loose grains or globules may adhere to the roof, but there is rarely a scale of coke, though such a scale is often attached to the bottom side of a collar.

Near the point of origin, on the reverse side of props or collars (facing away from the source of explosion) there are usually only a few scattered particles of coke, unless some reflex action has had effect.

The above-mentioned effects are those usually noted in room and pillar workings, in the room or in the entry where the explosion originated. After the explosive wave has passed from the room into the entry, or, if it originated in the entry, has traveled along it a few hundred feet, it gathers headway, and, provided it still has dry and pure enough coal dust to feed upon, forms thinner and more scattered coke scales. As the velocity of the explosive wave increases it no longer deposits coked dust on the facing side of props or posts, collars, and rib projections, except occasionally as scattered particles, but forms thin scales, often bright, first on the under side of collars, where there are any, then on the reverse side of timbers or projections.

At this stage coke particles may be driven into facing crevices in the ribs or cracks in timbers.

It is quite usual for the projections facing the origin to be coated with unburned dust brought out from adjacent workings, after the explosive wave has passed, by the suction created by the depression that follows the wave.

As the explosive wave traversing the relatively narrow passageway becomes more intense, which it usually does if there is dry coal dust to feed upon, the timbers are frequently swept along by the advance air wave, so that their evidence is lost unless their former position can be definitely located.

As the explosive wave gains in velocity practically no coke is deposited in the main passageway traversed, and is then to be looked for in isolated splashes on the lee side of corners of crosscuts or other side openings on the coal rib or on timbers in these openings. Another place worth observing is the roof behind such corners, where careful search will sometimes disclose occasional particles adhering or hanging in separate globules.

In a wide-sweeping explosion that traverses the main entries the violence usually becomes so great that little or no coke is deposited there. This was notably true in the recent Primero explosion, in which, though abundant coke showed in the rooms and cross entries, only a few isolated particles (on outby facing exposures) were observed along the main slope or in the immediately adjacent openings for the inner 2,000 feet, and none at all were found by the author in the outer 2,000 feet traversed by the explosion. Despite this scarcity of coke evidence in the main slope, bodies that were found under a fall of rock at the mouth were burned. Also a brakeman who was on a motor trip of mine cars about 100 feet from the mouth of the slope, but who was in line with the slope, was slightly burned. A telephone post about the same distance away from the slope, but 30 feet off the direct line of it, had considerable coke scales adhering to the side facing the mouth.

The position of the scale on this post brings to attention the mode of deposition of coked particles when an explosion dies away, as in the instance described above. They are thrown upon the facing exposures. This fact was also admirably illustrated in the Primero explosion in a certain side entry (A–8 entry), into which a branch explosion wave penetrated about 1,800 feet from the main slope, and there died away at a wet place in the road. At this point the timbers were all standing and no violence was indicated. There was loose coke on the outby sides of the timbers. Several hundred feet out toward the main slope, where violence was shown, increasing toward the slope, the coke particles and scales were generally on the inby surfaces, or those facing away from the approach of the explosive wave. The coked dust is sometimes located on the facing side in very wide places, as in wide rooms where the velocity of the wave becomes less, from opportunity to spread laterally.

The fact that coke is not deposited where the sweep of the explosive wave is greatest is possibly accounted for by the extreme speed attained, which carries along everything loose. This action is shown by the scouring of the walls of the passageway. Facing edges are rounded off, sometimes as if by a sand blast. The coke particles may be reduced to fragments, and it is possible that the intensity of the heat may effect a more or less complete combustion of the fixed carbon of the dust and resultant coke.

Following such an explosion there is a continued outrush of burned gases, which often carry surplus dust and deposit it on the lee side of projections, sometimes covering the coke just deposited.

Succeeding this outrush there is a return rush to fill the vacuum caused by the cooling of the gases. The return wave if strong may pick up dust and redeposit it on the lee side of projections, or that side which faced the explosion.

It must be remembered that in nearly all extensive dust explosions an immense amount of dust is subsequently drawn out of the workings and also created by the violence of the explosion. Moreover, there is usually a great surplus along the pathway. In the average entry 6 by 9 feet in section about 7 ounces of pure coal dust per linear foot will if completely burned give the maximum explosive effect possible with the air present. (See pp. 45–46.)

Typical analyses of coke from dust explosions, compared with analyses of the coal as mined.

	Franklin No. 2 mine, Miller (B) seam, Johnstown, Pa.[a]			Primero mine, Las Animas County, Colo.[b]					
	1.	2.	3.	4.	5.	6.	7.	8.	9.
Sample as received:									
Moisture	1.28	0.71	1.38	1.91	3.47	3.54	4.13	4.99	6.62
Volatile matter	19.88	11.09	8.48	32.27	[d] 21.23	24.53	18.38	12.68	20.49
Fixed carbon	68.11	67.65	[c] 52.59	57.21	31.17	42.97	58.12	45.22	55.66
Ash	10.73	20.55	37.55	8.61	44.13	28.96	19.37	37.11	17.23
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Moisture and ash free:									
Volatile matter	22.60	14.09	13.89	36.06	40.51	36.34	24.03	[e] 21.90	26.91
Fixed carbon	77.40	85.91	86.11	63.94	59.49	63.66	75.97	[e] 78.10	73.09

[a] Samples taken following an explosion October 31, 1909.
[b] Samples taken after explosion January 31, 1910.
[c] In this specimen of coke there appears to have been considerable combustion of the fixed carbon.
[d] Probably contains water of crystallization of clay in ash, thus affecting carbon-volatile ratio as determined by proximate method of analysis.
[e] This carbon-volatile ratio is interesting as indicating more complete combustion where the explosion died away. The ash content is also higher than that of coke samples near origin.

1. Coal from face, sample of full section as mined.
2. Thick coke scale from car bumper.
3. Coke scale adhering to rib in tenth heading.
4. Coal from face of room 2, 11-A entry, sample of full section of seam as mined. (Lab. No. 10063.)
5. Road dust from room 47, 7-A entry (beyond area affected by explosion). (Lab. No. 10052.)
6. Sample of dust from large mass in last crosscut, between entries 11-A and 12-A, close to their faces. Probably deposited by wave following the explosive wave. (Lab. No. 10051.)
7. Coked dust from prop in room 6, 11-A entry. (Lab. No. 9949.)
8. Coked dust from post in 8-A entry about 1,600 feet from main slope. (Lab. No. 9947.)
9. Coked dust from prop in last crosscut between entries 11-A and 12-A. (Lab. No. 9948.)

SPECIAL FEATURES IN DUST EXPLOSIONS.

At the face of headings or rooms what has been termed stalactitic carbon is found hanging in long threads from the roof. This is evidently the result of an insufficient supply of oxygen to allow complete combustion, and of subsequent deposition in still air.

In the typical explosion the great variation in the manifestation of heat is one of the curious features. At one point the heat appears very intense, at another there appears to be a complete dying away of the flame. Every observer has noticed that at certain points, where there can be no question that the flame has passed, blasting powder in cans has not been ignited. In some instances the powder has been upset on the ground and the grains scattered, but it has not always been burned. The upsetting may have been done after the passing of the flame by the subsequent rush of gases. It very frequently happens that an explosion passes by brattice cloth or sight strings (for alignment of entries) without igniting them. One obvious reason is that such cloths are generally damp and the time of exposure is momentary. Another reason is that immediately preceding the flame there is undoubtedly an air wave, which throws any loose canvas or string flat against the roof or ribs. In the majority of explosions it appears that the flame rarely fills the entry from side to side, but zigzags along, more or less in the center of the entry, striking the walls only here and there. This is also the manifestation in the Pittsburg gallery when mine road dust with high ash content is used and the flame is partly blanketed by the excess of ash.

The belief has prevailed very generally among mining men that because a dust explosion is usually manifested in the intake entries the explosion "feeds on the fresh air" or advances against the air current. When it is considered that the oxygen content of the return air of the average mine in this country rarely shows a decrease of more than one-half of 1 per cent of oxygen from the normal, and that the combustion of coal dust would not be seriously affected unless the deficiency exceeded 2 or 3 per cent or possibly more, it is clear that there can be little real basis for this impression. In this same connection, the idea has also been expressed that the fan was blowing in fresh air for the explosion to feed upon, and that this accounted for the greater destruction at the intake frequently manifested. When it is considered that the speed of a dust explosion, measured over only a short distance from the origin, as indicated by the Altofts experiments, is 1,400 feet per second, a rate presumably less than when the explosion is under greater headway, and, on the other hand, that the speed of the ventilating current would be at most one-sixtieth part of that rate, it is obvious that the fresh air introduced during an explosion can not play any part in its propagation, except by the momentary mechanical pressure required to overcome the inertia of the air current. The fact that a dust explosion does usually seek the intake entries is due to another cause, namely, that the fresh air has dried the coal dust along the roads, whereas in the return air way of mines of any size the air current, being saturated with water vapor, has no such drying effect.

The presence of the dust is the all-important thing. This was peculiarly obvious in the Primero mine explosion, where certain intake entries on which there was no haulage and which were free from dust showed no manifestation of the flame having passed through them.

In general, dust explosions are apt to die away on long stretches of wet ground, along which the ribs are also damp. However, if there has been much dry dust in that part of the entry nearer the origin, the blast may carry the dust through the wet zone and in this way continue the explosion beyond the area where it is not fed with fresh dust. Just what length of wet zone is essential to stop an explosion depends upon the violence of the explosion wave and the amount of dust carried in advance. Much is yet to be learned on this and other points from the experiments now being made here and in other countries. It should always be borne in mind that though coking is a conspicuous result of a coal-dust explosion in coking-coal mines, in mines producing coals that do not coke freely, such as those in the interior fields, or that do not coke at all, such as the lignites of the far West, few signs of coke or in the latter case none at all will result from an explosion. In such mines the dust will show a loss in volatile matter and an increase in ash; the chemical analysis must therefore furnish the clue as to the part played by dust.

Dust from black lignite or subbituminous coals, under some conditions, has proved to very explosive. For instance, in the Gallup, N. Mex., subbituminous field, violent explosions have resulted from blown-out shots. Coals of this field do not coke at all, and the mines are generally free from methane.

In the absence of the coking phenomenon, an explosion of considerable magnitude must be traced by the effects of flame and of violence. The former are particularly erratic in dust explosions, as previously indicated, for often such explosions traverse long distances without leaving signs of heating. This is probably due to several causes—the speed attained by the flame, the excess of dust over that needed for propagation, and the blanketing effect of the rock dust that is present. It is probable that where extreme speed is reached the flame darts only through the center of the dust cloud, borne by the advance wave. When the explosive wave reaches an enlargement of the passageway or where side passageways lead off, giving a large volume of air space, the excess dust may have opportunity for more or less complete combustion, giving a sudden burst of greater energy. Many observers have commented on the great explosive force often manifested at turnouts, overcasts, and sidings.

Probably the most sensitive record of heat is provided by the hair of victims. On the other hand, the observation of the writer is that damp paper and cloth are resistant to the quick flame of the explosion. When combustible material like loose paper is found in the path that had been traversed by the explosion, careful consideration is necessary to determine if it might not have been brought out from its former resting place by the depressive wave following the cooling of the burned gases. In the interior fields, where the practice prevails of taking 25-pound kegs or cans of black powder into the mines, the writer has observed, after a number of dust explosions, empty kegs that had been drawn out from the room gobs into the entry through which the explosion has traversed, though the explosion evidently did not enter the rooms.

Coal-dust explosions show little violence near the point of origin unless originating from the ignition of a considerable volume of fire damp or from the discharge of a large quantity of explosive.

The characteristic dust explosion increases in violence as far as the dry, inflammable dust extends, until the entrance of the mine is reached, unless there are retarding influences like long, wet areas or areas containing an excess of shale or rock dust.

LABORATORY INVESTIGATIONS OF THE IGNITION OF COAL DUST.

By J. C. W. Frazer.

INTRODUCTORY STATEMENT.

Although perhaps laboratory experiments had no great share in bringing about the general knowledge of the explosive character of coal dust, they are a valuable means of gaining information in advance of experiments carried out on a scale large enough to simulate mining conditions. The acceptance of the theory has come about only through such large-scale experimental work, which has shown conclusively that coal dust alone may be the cause of serious disasters or may propagate and prolong a comparatively harmless explosion caused from some other source, so as to produce a disaster extending through great areas.

The object of this part of the report is to describe in some detail the work which has been done on a laboratory scale bearing on the question of coal-dust ignition and inflammation. Many of the experiments on a somewhat larger scale are excluded, but some such early experiments are mentioned because of their historical interest and some of the most recent on account of their great importance in furnishing quantitative data.

EARLY EXPERIMENTS OF GALLOWAY.

Galloway[a] was one of the first to study this question from the experimental side. His experiments were carried out in a wooden box 5.71 meters long and 0.305 by 0.0152 meters cross section, through which a regulated current of air was passed. A hopper placed at one end served to introduce the dust, which was then carried by the air current 2 meters to a naked flame. Two kinds of coal dust were used, of the following composition:

Composition of coal dusts used in Galloway's experiments.

	1.	2.
Carbon (C)	85.3	82.6
Hydrogen (H_2)	5.0	5.4
Oxygen (O_2)	1.3	1.6
Nitrogen (N_2)	.6	1.0
Sulphur (S)	.7	.8
Moisture	.6	.7
Ash	6.5	3.5
Volatile matter	22.0	15.0

Galloway's first conclusion is thus stated by him:

> The results of these experiments and others which I have since made indicate in a conclusive way that a mixture of air and coal dust is not inflammable at ordinary atmospheric pressure.

However, on investigation he concluded that suspended coal dust could cause the explosion of a mixture of air and amounts of methane too small to be explosive in the absence of the dust.

IGNITION OF DUST FALLING ON FLAME.

Marreco and Morison[b] record certain crude observations made by persons whose names are not given, in which the tendency of coal dust to inflame was studied by allowing 5 liters of the powder to fall from a height of 6 meters upon a strong gas flame and noting the effect. Some of the dusts were ignited, and flame emitting much heat rose at times to a height of 10 meters. Other dusts were less inflammable, while still others failed to ignite at all. Professor Abel made certain experiments on ten different samples of coal dusts in an apparatus similar to that used by Galloway, with results entirely negative.

[a] Proc. Roy. Soc. London, 1876, p. 168; Annales des mines, ser. 7, vol. 11, 1878, p. 229; Bull. Soc. ind. minérale, ser. 2, vol. 6, 1877; vol. 7, 1878, p. 617; vol. 9, 1880, p. 157.

[b] North of England Inst. Min. and Mech. Eng., 1879, p. 92.

EXPERIMENTS OF VITAL.

While investigating the cause of a certain mine explosion Vital[a] concluded that coal dust had been an important factor in the accident, and he accordingly began certain laboratory experiments to see if it were not possible to ignite coal dust.

His apparatus (fig. 5) consisted of three parts—an explosion gallery, a gas burner of special construction, used as the source of ignition, and a device for measuring the violence of the explosion. The explosion gallery was a straight glass tube (*g*) 3.5 centimeters in diameter and 2 meters long. The end of this tube at which the ignition took place was somewhat enlarged, the opposite end somewhat constricted. Along the outside of this glass tube was pasted a strip of paper marked in 2-centimeter divisions in order to measure the distance to which the flame was propagated. Inside of the tube, at distances of 1.5 to 1.75 meters from the larger end, were placed small pieces of lead wrapped in paper to serve as indicators of the character of the flame traversing the tube. The ignition was brought about by

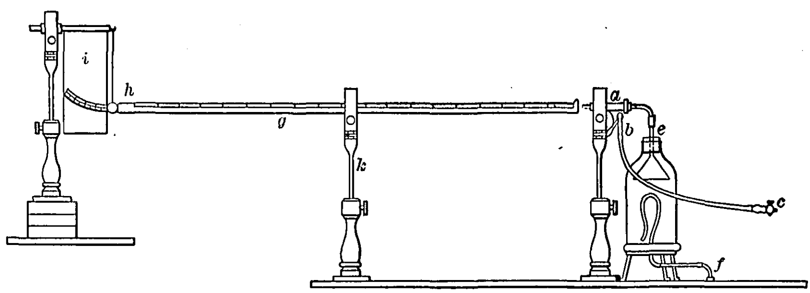


FIGURE 5.—Coal-dust ignition apparatus of Vital.

means of a specially constructed gas burner (*b*) situated at the larger end of the gallery tube. The gallery was movable, so that the flame from the gas burner could, at the proper instant, be directed momentarily into the larger end of the glass tube along its axis. This gas burner was operated by a foot bellows (*f*). Intervening between the bellows and the lamp was a glass reservoir into which the air entering from the bellows was directed toward the bottom. By this arrangement the gas burner could be operated by pure air by direct connection with the bellows or it could be fed by a dust-laden atmosphere by placing dust on the bottom of the reservoir beneath the opening from the bellows. At the opposite end of the gallery was placed the arrangement used for estimating the violence of the explosion in the gallery. This consisted of a light pith ball (*h*) 2 centimeters in diameter, the surface of which was coated with a layer of ivory black. This ball was placed against the open end of the gallery and rested against the front of a graduated circle (*i*), the divisions on which were 2 degrees each.

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[a] Annales des mines, ser. 7, vol. 7, 1875, p. 180.

Before the apparatus was used the following facts were ascertained: With the gas unlighted, the air blast carrying coal dust laid a heavy deposit of it on a porcelain plate set a few centimeters from the end of the tube. With the gas lighted, burning with pure air, the burner gave a blue flame, scarcely visible, 5 centimeters long. When the blast was operated with air containing coal dust in suspension a bright blue flame was obtained which showed many brilliant sparks of burning carbon, but did not deposit soot. With the two indicators in position, the gallery free from dust, the flame of the lamp fed by dust-laden air and directed into the gallery, the flame did not change color, but elongated about 2 centimeters. The indicators were not charred; the pendulum recoiled, but without shock.

These preliminary facts having been ascertained, the gallery was charged successively with dusts 1, 2, 3, and 4. When the dust-fed flame was directed into the tube, a red flame traversed the gallery rapidly, and the tube was left filled with fumes. After these were removed the walls were found to be covered with a coating of dust impregnated with water and bituminous matter. The indicators were burned, and the pendulum received a shock. The results of these experiments are given in the following table:

Results of Vital's experiments.

Observations.	Dust 1.	Dust 2.	Dust 3.	Dust 4.
Flame:				
Length	1.78 m	1.46 m	0.15 m	1.73 m.
Conduct	Regular	Regular	Regular	Regular.
Color	Red without brilliant particles.	Red without brilliant particles.	Blue and red without burning particles.	Red without brilliant particles.
Indicators:				
No. 1	Burnt	Burnt	Intact	Burnt.
No. 2	do	Charred	do	Do.
Angular motion of pendulum.	14°	11°	2°	13°.

Dusts 1 and 2 when removed from the tube had lost their black color and become reddish. No crystalline particles were observed, but globules composed largely of water were found on the inside of the tube. The crucible tests on these dusts before and after the experiments gave the results contained in the following table:

Analyses of dusts before and after ignition in Vital's experiments.

	Dust 1.		Dust 2.	
	Before (*a*).	After (*b*).	Before (*c*).	After (*d*).
Moisture	0.31	11.3	0.29	9.7
Dry dust:				
Volatile matter	34.1	21.2	34.8	23.5
Ash	24.2	29.7	24.4	28.2
Fixed carbon	41.7	49.1	40.8	48.3
	100.0	100.0	100.0	100.0

The coke residues from *a* and *c* were hard and brilliant, while those from *b* and *d*, collected after the explosion, were found to be pulverulent. A sample of reddish dust charred by an explosion in the mine from which the dusts used in the experiments came gave the following analysis:

Analysis of coal dust charred by mine explosion.

Volatile matter	27.2
Ash	26.1
Fixed carbon	46.7
	100.0

The conclusions reached as the result of this and additional experiments were:

(1) Certain finely divided dusts, rich in gas, take fire when brought into the air by a blown-out shot. These dusts, being decomposed, yield an explosive gas mixture which would take fire from the powder.

(2) The flame is instantaneous; it burns or alters the small amount of coal dust raised in its path and goes out.

(3) The intensity of the phenomenon is intimately connected with the character of the dust and becomes practically nil if the size of the particles is increased to an appreciable part of a millimeter.

(4) Other things being equal, the violence of the explosion would depend essentially on the physical conditions which determine the raising of the cloud of dust and its subsequent conduct.

(5) The presence of an excess of free carbon in the powder facilitates the production of an explosion.

Certain experiments were performed by the Societé de l'Industrie Minerale in a gallery used for testing lamps. During the experiments an air current was kept circulating through the apparatus. The inflammation was produced by igniting 50 grams of powder contained in a lead cartridge, after coal dust had been placed in the gallery. A second series of experiments was made in a gallery constructed for the purpose, the length of which could be varied. In this set of experiments the ignition charge was 30 grams of powder placed on the bottom of the gallery in a paper or lead cartridge.

In the first series of experiments it was noticed that the flame from the powder was elongated from 3 meters to 6½ meters. In the second series, when the gallery was 4 meters long and the ignition charge was placed 2 meters from the orifice a large flame shot out of the tube on the ignition of the charge; when the gallery was 8 meters long the flame did not emerge. Thus they were able to secure the ignition of the coal dust in this way, but the amount of such ignition must have been small, as paper was not ignited at 3 meters from the cartridge.

EXPERIMENTS OF HALL AND CLARK.

Hall and Clark [a] performed certain special experiments to study the effects of blown-out shots. They were the first to carry out experiments under conditions approaching those existing in mines. They ignited various charges of powder at the bottom of an inclined gallery along which was placed the coal dust under investigation. The length of the flame was determined by suspending pieces of inflammable cloth at regular intervals along the gallery. In many of their experiments the flames were voluminous.

This work is mentioned in more detail elsewhere, and is repeated here merely because it forms the beginning of the great amount of work which has been done on an extensive scale, and because it was repeated on a smaller scale shortly after by Marreco and Morison.[b]

These investigators carried out experiments on a much smaller scale than those of Hall and Clark, but otherwise there was some similarity in their method of working. The apparatus used consisted of a long rectangular box divided longitudinally into two compartments by a vertical partition reaching nearly to the bottom of the box. One of the longitudinal chambers thus formed was 3.6 meters long, the other 3 meters. One end of the apparatus was closed, and at the second end of the longer gallery was attached a connection for introducing a regulated current of compressed air. The second end of the shorter gallery was left open. Two small cannons were placed at the closed end, each directed along the axis of one of the galleries. They were discharged electrically and the connections so made that they could be fired either simultaneously or one at a short interval after the other. The air current which came into the longer gallery passed under the partition and through the shorter one and had a velocity of $1\frac{1}{2}$ to 3 meters. The charges of powder used were not given, nor the composition of the coal.

The results of the work showed that dusts conducted themselves very differently under these conditions, according to their nature. With some the flame issued from the box, with others the flame was only a small fraction of the length of the box. The greatest effects were produced when the cannons were fired at short intervals apart, the first shot serving to charge the air of the second gallery with dust. The shot then fired into the second gallery produced more violent explosions. In many of their experiments the box was burst open.

As the result of these experiments they concluded that if they had been able to perform their experiment on a sufficiently large scale, the results would have been comparable in every way with a mine explosion.

[a] Communicated to the North of England Inst. Min. and Mech. Eng., June, 1876.

[b] North of England Inst. Min. and Mech. Eng., 1879, p. 85; Annales des mines, ser. 7, vol. 15, 1879, p. 374.

EXPERIMENTS OF ABEL.

Abel[a] attempted to secure the explosion of coal dust on a small scale by means of a charge of 26 grams of powder placed on the bottom of a wooden box, which was used as the explosion chamber. He judged the effect of the dust by the extent to which the flame of the powder was elongated by the burning of the dust. His results were negative, as the length of the flame was sometimes longer but sometimes shorter than the flame of the powder alone. But he concluded that possibly with the large flame and violent agitation from a blown-out shot dust alone would propagate a flame farther than the experiments on a small scale seemed to indicate.

EXPERIMENTS OF MALLARD AND LE CHATELIER.

In 1882 Mallard and Le Chatelier[b] published the results of their work. In the course of this work the authors undertook a study on a laboratory scale of many of the important conditions influencing the ignition and the explosive character of coal dust. This work is of great historical interest, because of the conclusions reached by its authors and the influence which these conclusions have exercised in the development of the coal-dust theory. The work is also of great scientific interest because of its scope and the number of problems of a fundamental character which the authors have undertaken to investigate. Their experimental work is prefaced by a summing up of the evidence in support of the theory, both the evidence furnished by laboratory experiments and that obtained from mine accidents where coal dust had been assumed to be a factor.

Their own laboratory experiments are divided in the following way:

Chapter I. The study of the phenomena presented by the mixture of coal dust and air containing no methane.

Chapter II. The study of the phenomena presented by mixtures of coal dust with air containing an amount of methane too small to form an explosive mixture.

Chapter III. The study of the phenomena presented by mixtures of coal dust with an explosive mixture of air and methane.

Our interest in this work, for the present, centers in Chapter I. This chapter is subdivided into the following six sections:

Section 1. A study of the influence of the size of the flame.
Section 2. A study of the influence of the velocity of the air current.
Section 3. A study of the influence of the size of the dust particles.
Section 4. A study of the influence of the nature of the coal.
Section 5. A study of the influence of the relative proportions of dust and air.
Section 6. The velocity of propagation of the flame.

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[a] Annales des mines, ser. 7, vol. 20, 1881, pp. 121–159.
[b] Idem, ser. 8, vol. 1, 1882, pp. 5–98.

The experiments were made in two forms of apparatus. The first resembled that previously used by Galloway, Morison, and Abel. It consisted of a wooden box, 4 meters long, 0.4 meter high, and 0.15 meter wide. One extremity communicated with a ventilator capable of giving a pressure of 5 centimeters of water. At 50 centimeters from this end was a device to regulate the flow of air, the velocity of the ventilator being maintained uniform. At a point 25 centimeters farther there was placed on top of the main box or gallery a second box, perforated for the introduction of coal dust. The arrangement of the regulator with reference to the point of introduction of the dust was such that the eddy produced at the regulator served to disseminate the dust through the air. At 2 meters farther a removable glass window was placed, which permitted the introduction of a lamp and the observation of the results. The other end of the gallery was open to the outside air, 50 centimeters beyond this window. When the dust burned it gave a large flame, filling the whole section and extending out of the orifice.

The second form of apparatus used was simply a cubical wooden box of 50-centimeter dimensions. At the center was placed a gas flame directed downward in order to spread it out. In testing the dust in this form of apparatus a double handful of the dust was held about 1½ meters above the box, and was allowed to fall between the fingers in such a way as to subdivide it as much as possible. In falling the columns of descending dust carried along a considerable amount of air by the time the dust reached the flame, and the eddy produced in the box by this air kept the atmosphere charged with the dust. If the sample was inflammable, it ignited at the gas flame.

The sources of heat investigated by the authors were, first, the normal flame of the Davy lamp; second, the same after regulating its flame to a height of 5 centimeters; third, a large gas flame; fourth, a large roll of burning paper.

With finely powdered coal of an inflammable character it was found that in the first form of apparatus described above inflammation took place instantly when the last three sources of heat were used. With a normal flame of the Davy lamp flashes occurred, after which the whole was inflamed, the duration of this phenomenon being only about two seconds.

Coal dust collected in the gallery of the same mine, but less finely divided, took fire immediately on contact with the gas flame and roll of burning paper, and after the end of some seconds it ignited from the flame of the Davy lamp, burning 5 centimeters high. But with the normal flame of the Davy lamp, ignition occurred only after some time, or not at all.

The coarser dust collected from the floor of a gas works ignited after some seconds from the third and fourth sources of heat, but not from the others. Another sample of a different dust was found to be inflammable from all four sources.

The conclusion of the authors was that an inflammable mixture of coal dust and air required for its ignition a flame of a certain minimum volume, varying with the nature of the dust. The same is true of explosive mixtures of gases ignited by an electric spark, a certain minimum spark being necessary, varying with the character of the gas mixture. The great difference is the enormous size of the source of heat necessary to ignite the dusts as compared to the electric spark. By increasing the size of flame above this minimum the rapidity of inflammation is increased and for a certain volume becomes practically instantaneous and nothing is gained by increasing the size of the flame beyond this volume. This maximum volume seemed to be less than a cubic decimeter for the dusts investigated.

Some indication of the effect of the size of the dust particles is seen from the above-described experiments, in which it was found that the more finely divided were the dusts the more inflammable they became and the smaller was the size of the flame necessary for their ignition. Yet in many tests these authors thought that fineness of division was a secondary matter. Some coals were found inflammable whatever the size of the particles. This fact is not opposed to the principle of greater inflammability of finely divided coals, for the authors explain that the dusts used by them were not screened to a certain size, and in all samples there was a sufficient amount of the fine dust that remains longest in suspension to cause ignition on arrival at the source of heat. In this way the occurrence of fine dust in a sample, the average size of whose particles was large, would mask the effect that might be anticipated from the relatively large average size of the particles. For instance, two samples of dust may be very different with respect to fineness when introduced into the apparatus, but in the course of their passage to the flame, situated some distance away, the largest particles are deposited and only the particles smaller in size reach the flame, so that at this point both dust clouds are very similar as regards the size of the particles remaining in suspension.

The velocity of the air current which carried the dust in suspension was found to have a great influence on its degree of inflammability. One of the samples studied ceased to inflame for velocities under 1 meter or above 4 meters. The reason appeared to the authors to be that with the weak air current dust was deposited from suspension before reaching the flame, while with currents faster than 4 meters the particles traversed the flame too rapidly to become ignited.

In the course of the experiments mentioned above the authors established the fact that dusts of certain coals might be considered inflammable while others yield noninflammable dust. Many authors have previously attempted to connect the inflammability of the dust with the gaseous character of the coal from which it was derived, without, however, giving any experimental evidence of such connection. The authors took up this question and employed for the investigation both forms of apparatus described above, after having shown previously that the behavior of each dust was similar in both forms of apparatus. As a result of this investigation the authors were able to arrange the coals investigated into two groups, first, those whose dusts were inflammable, second, those whose dusts were noninflammable. These results are summarized as follows:

Percentage of volatile matter in inflammable and noninflammable dusts.

Inflammable dusts:		Noninflammable dusts:	
Sample 1	32.0	Sample 1	19.5
Sample 2	35.0	Sample 2	24.6
Sample 3	39.0	Sample 3	19.0
Sample 4	50.0	Sample 4	18.0

In stating their conclusion the authors say that a coal to yield an inflammable dust must contain 30 per cent or more volatile matter. The last sample investigated was a lignite, containing 50 per cent volatile matter. It was also found to be the most inflammable of all.

In stating that a coal dust is noninflammable the authors do not mean that the coal dust does not burn, but that under the conditions of the experiment the dust suspended in the air is not capable of propagating the combustion much beyond the confines of the source of inflammation. The propagation of the flame they consider to be a complex function of the temperature of combustion, of inflammation, of distillation, etc. It is conceivable that this combustion could be arrested under certain conditions and that the air and dust mixture would not inflame, while in other circumstances it would burn more or less easily. It is for an analogous reason that a mixture of air with methane in amounts insufficient to form an explosive mixture can be rendered explosive merely by raising somewhat the temperature of the mixture. The dusts of all coals are certainly combustible under the proper conditions, but only a certain number are inflammable under the conditions set by the authors. The proportion of volatile matter, according to the authors, is not the only cause of the inflammability of coal dust, as they consider that those volatile constituents which have already been partially oxidized would be expected to be more inflammable than those same substances unoxidized, just as alcohol vapor is more inflammable than vapors of petroleum. In other words, the authors believe that the inflammable character of the coal dust depends not only on the amount of volatile matter contained in the coal, but also upon its character. A further influence on the inflammable nature of a coal dust would be the ease with which the volatile matter is expelled.

The authors confirm the conclusions of Galloway that the amount of dust suspended in the air must be considerable to render the mixture inflammable—that the dust clouds should be very dense, such that a thickness of 50 centimeters of the mixture in bright daylight intercepts completely the light from a candle placed in it. The authors made no special measurements in this connection, but conclude from their experience that Galloway was correct in assuming that the amounts of suspended dust most likely to give an inflammable mixture would be 1 kilogram per cubic meter of air.

Berthelot has stated that such an excess of dust is necessary because the only part of the dust particle that enters into action is its surface, whereas in gases the mixture exploding most violently contains the constituents in proper proportions for complete combustion.

The authors consider that to put in suspension such a quantity of dust and keep it suspended would require a violent agitation in the air, because the density of such a mixture is nearly double that of the pure air, and hence only a considerable force can overcome the tendency of the two to separate; besides, the dust would be deposited soon after the cause of agitation ceased. As previously mentioned, the authors show that according to their experiment a velocity of 1 meter a second is not sufficient to keep the air charged to the point of inflammation.

In studying the velocity of propagation of the flame the authors attempted to use the same method by means of which they measured the velocity of propagation of the flame in gas mixtures, but they found that in mixtures of coal dust and air not much agitated there was no appreciable velocity of propagation of flame, and conclude that if it exists it must be less than 1 centimeter. The propagation appears to be effected by the internal movements of the air instead of by conductivity or radiation.

When the air and dust mixture is agitated by considerable internal movements, the velocity of propagation is still small, less than 1 meter, which shows the great difference between the velocity of such a flame and that in an explosive mixture of gases. In confirmation of this statement the authors call attention to the fact that when coal dust was ignited in their long apparatus a sheet of paper which covered the hole in the side of the gallery was not broken and was scarcely puffed out by the pressure within.

In applying their results to mining conditions the authors say that the accidents that can be attributed to dust alone are very rare, not dangerous, and that the flame does not extend farther than 50 meters. The dangerous explosions occur mostly in gaseous mines, and whether the dust is inflammable or not the conditions do not permit doubting the presence of methane. Lignite mines which are slightly gaseous, if at all so, but which contain dusts more inflammable than coal dust, have never suffered from serious explosions. Further, all the accidents attributable to dust alone are caused by blown-out shots directed to the floor of the mine. The results of their experiments have confirmed these facts by showing the reason for them—the slight inflammability of the coal dust.

According to Galloway and to Mallard and Le Chatelier, the quantity of dust which must be suspended in the air to give an inflammable mixture is far beyond what could possibly be in the air even in the most dusty parts, and it requires a very violent agitation to bring such an amount of dust into the air and maintain it in suspension. Further, the authors have shown that dusts are precipitated very rapidly from the air whenever the causes which brought them into the air cease to operate. Their experiments on the velocity of propagation of the flame in air and dust mixtures show it to be practically zero. These two facts tend to limit the extent of a dust explosion, because before the flame can travel an appreciable distance there ceases to be a sufficient amount of dust suspended in the air to propagate the inflammation. They conclude, therefore, that coal dust alone is of very little danger in mines, but in the presence of small amounts of methane the danger is much increased. Coal dusts play an important part in mine accidents only by lowering the explosive limit of an air and methane mixture.

LATER EXPERIMENTS BY GALLOWAY.

After his first investigation on the question of the explosion of mixtures of air and coal dust, Galloway performed a number of other experiments, as a result of which he altered his first opinion, which was stated above in discussing his work. His first conclusion was that coal dust, to be a factor in mine explosions, must be suspended in air that contains at least some methane. His later work led him to the conclusion that coal dust alone mixed with air would under the proper conditions form an explosive mixture, and that in all probability it figured at times as the sole cause of certain mine explosions.

EXPERIMENTS OF THORPE.

From this time on work on the question of coal-dust explosions was done on a comparatively large scale. Interest was then taken in the matter by several European governments, and special commissions were appointed by these to investigate the question by instituting experiments to demonstrate conclusively the explosive character of a mixture of pure air and coal dust. These experiments have been discussed in another portion of this bulletin. Before describing certain experiments carried out under conditions which have been particularly well controlled attention will be called to several demonstrations of the explosive character of coal dust made on a laboratory scale as lecture experiments. A number of such experiments have been described, and of these one described by Thorpe,[a] with which it is possible to illustrate many features of a dust explosion, will be taken up first.

The apparatus (fig. 6) consists of a long wooden gallery in two parts, A and B, which together are 3.66 meters long, each 12.7 centimeters square in cross section. These two parts fit into opposite sides of a similar gallery (C) placed at right angles to A and B and intended to represent a second gallery of a mine crossing the main one at right angles. Each of these galleries is covered for its whole length by a hinged top in two parts, which during the experiment are tightly clasped down. The box should be made of 1-inch oak and screwed together. A shutter (*a*) fits in the slot *s*. This end of A slips into

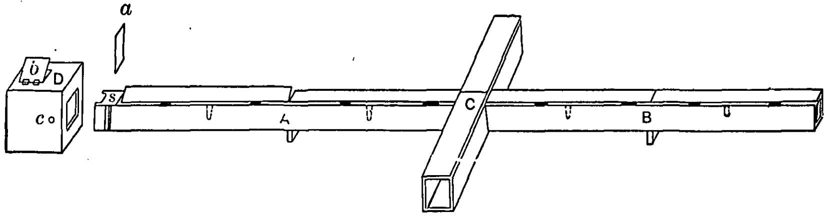


FIGURE 6.—Coal-dust ignition apparatus of Thorpe.

a quadrangle box D, 22.86 centimeters square, which is provided with a door (*b*) and a small hole (*c*), through which a tube can be inserted.

The coal dust is put into the box D and a blank cartridge is fired from a small pistol through *c*. The dust raised by the concussion ignites from the flame of the powder, and the flame of the burning dust goes several feet out of the ends of the box. To illustrate the effect of a local explosion of methane, D is filled with an explosive mixture of methane and air, with *a* in place; *a* is then withdrawn and a flame applied at *c*. The resulting gas explosion charges the air with dust and ignites it, and the flame rushes along the gallery and shoots out at the end, being propagated the length of the gallery and 4 or 5 feet out into the air. The success of the experiment depends on the nature of the coal dust and the character of the initial cause. Some dusts are not brought into the air by concussion and the flame soon dies out. The condition of the coal dust with respect to dryness and fineness of division has a great influence on the character of the explosion.

[a] Jour. Chem. Soc., vol. 61, p. 414.

By the use of lycopodium powder instead of coal dust one can show in this apparatus many things observed in mine accidents. For example, it is possible now to trace an explosion to its source by the way the charred dust is thrown against the props in the mine. The deposition of dust is always on the opposite side from the explosion, because the eddies that exist at such points drive the dust to the rear of the object. By putting small pegs in the floor of the experimental gallery it can be shown that the lycopodium powder is swept away clean from in front of the pegs and heaped up behind them. It is also well known that dust explosions increase in violence with the distance from the source of the explosion. At the point of origin the disturbance is small, while a few hundred yards away the violence of the explosion is remarkably greater.

REDUCTION OF PRESSURE FOLLOWING EXPLOSIVE WAVE.

It has been said by some that mine explosions are frequently so violent that the diminution in pressure at places is great enough to draw out methane inclosed in the coal. This statement has obtained many believers. The only experimental evidence in regard to it was obtained by Greenwell.[a] The apparatus used for his experiment was a box closed at one end and open at the other. The box is 3 feet long, and at right angles to this and opening into it is another box smaller than the first and fitted with a valve on which the outside atmosphere acts. When a charge of dust was fired in this apparatus the violent outrush of air drew out some of the air in the small box connected to the side of the larger one, and the valve was driven in because of the diminished pressure produced in the small box by the withdrawal of a portion of the air which previously filled it at atmospheric pressure. This does not show a diminution of pressure in the main gallery, according to the author, as the position of the side box would cause the withdrawal of part of the air it contained by the principle on which an injector operates. By a special manometer, which he devised to show that an area of low pressure exists around the flame of a Bunsen burner, Thorpe was able to demonstrate that no diminished pressure exists along the side of the gallery during an explosion, but that on the contrary there was always considerable pressure against the sides and top of the box. Hence the statement that gas is brought into a mine from the face of the coal because of diminished pressure produced in certain areas during an explosion does not receive confirmation by this experimental work.

[a] Trans. Manchester Geol. Soc., vol. 10, 1870, pp. 20-27.

EXPERIMENTS OF ENGLER.

In 1907 Engler[a] published a description of a form of apparatus designed to demonstrate the explosion of coal dust on a laboratory scale. He showed that substances like bituminous coal, meal, and naphthalene, which are capable of giving gas, can be exploded by an electric spark. He showed also that substances such as soot and charcoal do not ignite in air alone, but will explode in a mixture of air with a small amount of combustible gas, even a mixture that would not ignite in the absence of the dust. Thus in air containing 2.5 to 3.5 per cent of methane the presence of soot or charcoal dust brought about the explosion of the mixture, and this explosion was increased in violence by the use of dust from bituminous coal. A bituminous coal dust that does not explode when mixed with air will do so if the air contain a small percentage of methane. The apparatus which Engler used to demonstrate the explosion of coal dust is shown in figure 7. A is a flask of 250 to 500 cubic centimeters capacity. A quantity of coal dust is put into B, a small amount of which can be introduced into A by elevating B. The wires *c c* lead from an induction coil, the spark gap being between the two platinum wires at *a*. By blowing air into *b* in jets from a rubber bulb the dust is brought into suspension, and as the cloud passes (*a*) the ignition of the dust takes place, if the dust is that of the proper kind of bituminous coal. In a similar piece of apparatus filled with a mixture of air and 2.5 to 3.5 per cent of methane, or even less, no explosion takes place when the mixture is sparked in the absence of dust, but on introducing a small amount of a coal dust that has been found to be nonexplosive, and blowing it into the air as before by means of a rubber bulb, the contents of the vessel explode with great violence, and the stopper is blown out of the vessel or the glass flask is shattered. The same is true when soot or powdered charcoal is used in place of the nonexplosive coal dust.

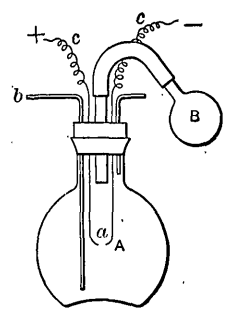


FIGURE 7.—Coal-dust ignition apparatus of Engler.

LECTURE EXPERIMENT OF BEDSON AND WIDDAS.

A simple lecture experiment to show the inflammable character of finely ground coal dust is described by Bedson and Widdas.[b] Their apparatus is shown in figure 8. It consists of two glass tubes, *a* and *h*, each 3.81 centimeters in diameter, *a* being 7.62 centimeters

[a] Chem. Zeitung, vol. 31, p. 358; Jour. für Gasbeleuchtung und Wasserversorgung, vol. 50, p. 488.
[b] Trans. Inst. Min. Eng., vol. 32, 1907, p. 531.

long and *h* 30.48 centimeters. The tubes *a* and *h* are connected by a collar (*f*) which holds in position the cotton gauze *e*, on which is placed a quantity of dust (*g*). Into the other end of *a* is fitted a stopper (*b*) through which passes the glass tube *c*, the upper end of which (*d*) comes a short distance below *e*. By means of an air blast blown through *c*, the dust is blown from the gauze and disseminated as a cloud, which is carried upward by the air blast to the open end (*i*) of the tube *h*. When a naked flame is applied to *i* the cloud of dust ignites and the flame of combustion travels down the tube.

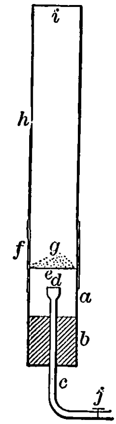


FIGURE 8.—Apparatus of Bedson and Widdas for use in lectures.

EXPERIMENTS OF HOLTZWART AND MEYER.

In 1891[a] the attention of Rud. Holtzwart and Ernst von Meyer was directed to an investigation of the cause of explosions which had occurred frequently in factories where lignite briquets are manufactured. The principal result of their work was a study of the explosive character of lignite dusts mixed with air. Their apparatus (fig. 9) consisted of an explosion tube (E) of 50 cubic centimeters capacity, having two platinum wires sealed through its side about midway the length of the tube. These wires (*i i*) are about 3 to 4 millimeters apart. The spark used as the source of ignition was obtained from an induction coil operated by two strong Bunsen elements. In one end of this tube (k_2) is fitted a one-hole rubber stopper, through which passes a glass tube bent downward at a right angle. The longer limb of this tube (*m*) is immersed under water. A weighed quantity of dust is placed against the stopcock H. A is a glass bottle of 600 cubic centimeters capacity; B, a bottle of 3 liters capacity. C is a reservoir of water placed at a height of 1.5 meters above the level of the water in B. In each of the experiments performed 0.18 gram of the dust was used. Water from the reservoir (C) is allowed to flow into B, compressing the air contained in B to a pressure equal to the difference in the level of the water in

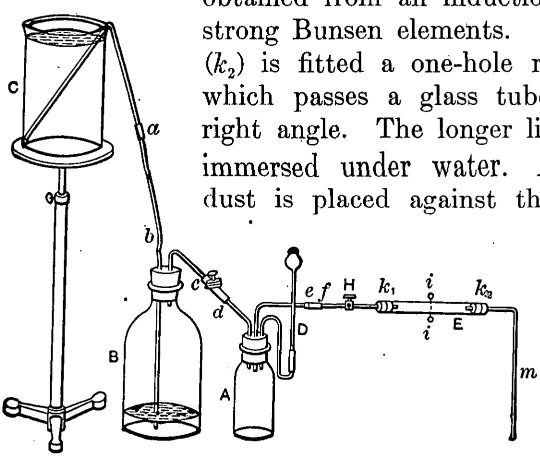


FIGURE 9.—Coal-dust ignition apparatus of Holtzwart and Meyer.

[a] Dingler's Polytechnisches Journal, vol. 280, 1891, pp. 185 and 237.

the two vessels. The screw cock *c* is then opened until the air contained in A is compressed to a definite pressure indicated by the manometer D. This pressure was varied in the course of study of each sample. After the proper pressure was secured in A and the apparatus was connected up as indicated, the passage of the spark between the terminals *i i* is started. H is then quickly opened and closed and the character of the explosion observed. The character of the explosion is indicated somewhat by the behavior of the water closing the open end of *m*.

Eight samples of dust were tested. The results of these experiments and the analyses of the dusts are given in the two following tables. The samples were collected from various parts of the briquetting plant, put through a fine sieve, and dried for a long time over sulphuric acid. To remove the last of the moisture the samples were heated to 60° or 70° before analysis.

Results of experiments by Holtzwart and Meyer with explosions of lignite dust.

Sample No.	Results of tests for specified pressures of air in A in centimeters of mercury.				Remarks.
	2 centimeters.	3 centimeters.	4 centimeters.	8 centimeters.	
1	2 negative, 1 very weak.	1 negative, 1 weak.	2 negative...	Negative....	Tendency to explode small; in 8 experiments 6 negative.
2	2 negative...	2 negative...	.....do......	.....do....	No explosion.
3	2 negative, 1 very weak.	.....do......	.....do......	.....do......	Dust not inclined to explode.
4	2 very violent.	2 very violent.	2 very violent.	2 very violent.	
5	2 negative...	2 negative...	2 negative, 1 weak.	Negative....	In 7 experiments 6 negative.
6	2 negative, 1 weak.	2 rather strong.	2 rather strong.	2 rather strong.	Sample inclined to explode; in 9 experiments 7 positive.
7	2 strong.....	2 strong.....	2 strong.....	2 strong.....	Dust explosion very strong.
8	2 strong, 1 negative.	.....do......	.....do......	.....do......	Do.

Analyses of lignite dusts used in experiments by Holtzwart and Meyer.

		Ash.	C.	H_2.	N_2.	S.	O_2.
1	Complete	15.93	56.93	5.16	0.93	4.13	16.92
	Ash-free	....	67.70	6.14	1.10	4.90	20.16
2	Complete	14.05	57.72	4.73	.74	3.16	19.60
	Ash-free	....	67.16	5.5	.86	3.68	22.80
3	Complete	9.44	60.76	5.22	1.15	2.00	31.43
	Ash-free	....	67.09	5.76	1.27	2.21	23.67
4	Complete	6.12	61.33	4.66	1.11	.63	26.15
	Ash-free	....	65.33	4.96	1.21	.68	27.82
5	Complete	7.08	59.56	4.53	1.22	.60	27.01
	Ash-free	....	64.10	4.88	1.33	.65	29.04

A glance at the above table shows a great difference in the conduct of the coals with respect to their inflammability. There is, however, no apparent connection between their explosive character and their elementary composition. Coal No. 4 is chemically very closely related to No. 5, but their conduct with respect to their explosive character is entirely different. It is probable that the imflammable character of the dust is related to the condition of the surface as well as to the bituminous matter of the coal. Coals Nos. 4, 6, 7, and 8 are seen by inspection of the analyses to be very explosive, while No. 5, chemically very similar to these, is not explosive. Nos. 2 and 3 were found to be nonexplosive, and No. 1 exploded only once. The character of the explosion could be judged by the eye. With Nos. 1 and 3, as propagation of the flame was very slow, its passage through the tube could be readily followed by the eye, appearing to have a velocity very much like that of propagation of a flame in a mixture of carbon monoxide and oxygen near its explosive limit; but in Nos. 4, 7, and 8 the explosion was sudden, and the whole tube filled with a flash of light. In case of such violent explosions much gas escapes from the tube (*m*), while in weak explosions no gas escapes. The experimenters failed to secure an explosion of lignite dust except when the dust was blown in as indicated above. When the dust was placed in the tube E, and the tube was shaken while the spark was passing, no explosion was obtained even with the most explosive dusts. This shows the great importance which the method of introducing the dust can exercise on the character of the explosion. To the authors the character of the explosion of lignite dust under these conditions appeared very similar to that of an explosive gas mixture.

In one experiment, A and E were filled with a mixture composed of 10 per cent carbon monoxide and 90 per cent air. This amount of carbon monoxide and air was just below the explosive limit for these gases. A sample of coal No. 4, which was one of the most explosive coals investigated, was exploded in this mixture. When the coal was blown into the apparatus the explosion which resulted was not noticeably stronger than when the coal was used with air alone.

Their study was confined entirely to lignites, but they considered that a similar study of bituminous coals would be of greatest importance in furnishing data regarding the explosive character of such coals.

They further investigated the gases which were evolved from lignites when heated. Even at 400° C. the gases which were given off were found on analysis to be in such small amounts and of such nonexplosive nature that they could not be considered as a source of the explosions which so frequently occur in briquetting plants; the real cause of the explosions, according to the authors, must be the coal dust.

LABORATORY EXPERIMENTS OF BEDSON AND WIDDAS.

Convinced of the utility of the method adopted by Holtzwart and Meyer in their investigations of the explosive character of lignite dusts, Bedson and Widdas[a] undertook a similar investigation of mixtures of coal dust and air. The apparatus they used for this work differed in certain respects from that used by Holtzwart and Meyer. In place of the electric spark used by those authors as the source of ignition they substituted in certain experiments a gas flame or a spiral of platinum wire heated electrically. The apparatus shown in figure 10 consists of a bottle (*a*) of about 1,900 cubic centimeters capacity, closed by a three-hole rubber stopper, through which pass three glass tubes (*b*, *c*, and *e*). The tube *b* was connected with a foot bellows, *c* with an open manometer (*d*), and *e* with the chamber in which the explosion takes place. This chamber in the first form of apparatus is a cubical tin box (*f*) of 10.16 centimeters dimension, provided with mica windows (*g*) at the front and back. On two opposite sides of the box are openings 3.81 centimeters in diameter, provided with collars permitting the attachment of the glass tubes *l* and *m*. The glass tube *e*, communicating with the bottle *a*, is provided with a stopcock (*p*) and was bent downward (inside of the glass tube *m*) at *n*, in front of which is placed the weighed sample of dust. Two other openings (*h* and *t*) into the top and bottom of *f* are for the introduction of the gas flame or other source of ignition.

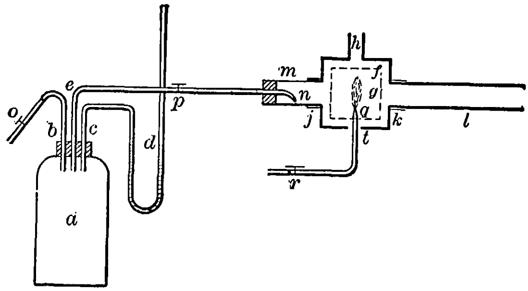


FIGURE 10.—First coal-dust ignition apparatus of Bedson and Widdas.

The operation is carried out in the following way: A weighed quantity of dust is placed in front of *n*, in the glass tube *m*. The air in the bottle *a* is compressed to the desired pressure by means of the foot bellows connected to *b*. After placing the gas jet (*q*) in position the stopcock *p* is quickly opened. The outrush of air from *e* blows the dust into the air and carries it to the source of ignition, where the behavior of the dust is observed through the windows. The first series of experiments was made on finely ground samples of lignite. The sources of ignition used were an electric spark, electrically heated platinum wire, and a small gas flame. The second series of experiments was a study of finely ground dust of each of the following materials: Brown coal, bituminous coal, dant (slack), charcoal, wheat flour, wood sawdust, lycopodium powder, metallic aluminum, and

[a] Trans. Inst. Min. Eng., vol. 32, 1907, p. 529.

metallic magnesium. The source of ignition used in each case was a small gas flame, the amount of dust 1 gram. In every material except dant and charcoal inflammation took place.

In a second paper[a] the same authors record the results of further experiments on coal dust with apparatus (fig. 11), somewhat different from that described above. In order to secure better control of the conditions of ignition they substituted a coil of platinum wire for the gas flame and electric spark used in some of their earlier experiments. They could in this way obtain a considerable range of temperature, and could measure approximately the temperature of the coil during any experiment by measuring the current passing through the coil. Below is given the current that was found necessary to produce inflammation of each of the dusts named:

Current required to produce ignition in specified dusts.

	Amperes.
Brown coal	10.5
Busty seam, bright coal	11.5
Hutton seam, coal	11.5
Lycopodium	11.5
Brockwell seam, cannel	12.5
Harvey seam, splint	17.0

A current of 17 amperes was insufficient to produce an ignition with anthracite or dant. The samples used in these experiments were passed through a 100-mesh sieve and were air dried. To show the effect of drying on the temperature of ignition of those same coals, experiments were carried out in the same way as those described above, except that the coals were dried. The results were as follows:

Current required to produce ignition of dried dusts.

	Amperes.
Brown coal	9.8–10.0
Busty seam, bright coal	11.0–11.5
Hutton seam, coal	11.0–11.5
Brockwell seam, cannel	11.5–12.6
Harvey seam, splint	13.0–15.0

Further experiments were made on the effect of moisture by exposing the coal dusts under a bell jar over water. Brown coal dust, after seventy-two hours' exposure, and Hutton seam coal dust, after ninety-six hours' exposure, required, respectively, 12.2 and 13.5 amperes. In another set of experiments, the freshly ground dust was mixed with water to a thin paste and allowed to dry for six days in the air. At the end of that time it was found to contain 3.1 per cent moisture, and to require 13.5 amperes for its ignition. The coal was mixed with water the second time and left to dry, and on the fifth day it was found to contain 3.77 per cent moisture, and to require

[a] Trans. Inst. Min. Eng., vol. 34, 1908, pp. 91–97.

13.8 amperes for its ignition. At the end of eight days it contained 1.78 per cent moisture, and required 13.8 amperes for its ignition. The conclusion of the authors regarding the effect of moisture on the inflammability of coal dust is that in order to prevent an ignition of an inflammable dust it must be made so damp that it can not be blown into the air as a cloud by a jet of air, but that an increase of moisture tends to raise the temperature of inflammation.

It was also found that exposure to air rendered freshly ground dust less inflammable. A sample of dust which in the beginning required 12.5 amperes for ignition required 14 amperes at the end of seventeen days.

Experiments were also made to test the effect of incombustible dusts on the inflammability of coal dust. The result of these experiments, summed up in the table below, was to show that the temperature of ignition of such a mixture was higher than that of the coal dust alone.

Effect of mixture of sand with coal dust on current required for ignition.

Character of coal.	Amount of sand to 1 gram of coal.	Current required for ignition.	Remarks.
	Grams.	*Amperes.*	
Brown coal	....	12.5	
Do	1	13	6 trials, 4 ignitions.
Do	1.5	13.5	4 trials, 3 ignitions.
Do	2	15.5	
Hutton seam	....	12.5	
Do	.5	13	
Do	1	14	
Do	1.5	14	
Do	3	15	No inflammation.

While these results afford evidence of the difference in conduct of different coals regarding their temperature of ignition, they give no measure of the relative inflammability of the dusts, as the only means available of judging the results was by the eye, and they could only be classified as no ignition, a slight puff, or a violent inflammation. An attempt was made by these authors to gain more exact information on this point with the use of the piece of apparatus shown in figure 11. It consists of the explosion vessel *a*, of 2 liters capacity, and provided with 3 tubulures, *b*, *k*, and *o*. In *b* is inserted a stopper, permitting connection to a coil of platinum wire (*f*). The dust is introduced through *k* in much the same way as in their first experiments, while *o* is attached to the apparatus used for registering the pressure developed in *a* by the inflammation of the dust. The apparatus constructed to register the pressure consists of a three-necked Wolff bottle, one opening of which is connected with the explosion vessel and the second with a closed manometer containing colored water. The third opening contains a glass tube, the upper end of which is closed by a short piece of rubber tubing and a pinch cock. Any sudden pressure generated in the explosion vessel produces a movement of the liquid in the manometer, the extent of which is noted by means of a scale attached to its side.

Equal weights of the same coal dust gave practically the same pressure in the apparatus. Equal weights of different dusts, when the same current was used for ignition, produced quite different pressures. These pressures, the authors consider, indicate the explosive character of the dust mixture. Several samples of dusts were examined in this way; some of these were collected from a mine, while others were ground in the laboratory. These are designated in the table below as natural and artificial dusts, and all were put through a screen of 100 meshes to the inch. The weight of dust used in each experiment was 2 grams, the pressure of the air used to project the dust into the vessel was 8 inches of mercury, and the wire was heated by a current of 15 amperes. The results are given in the following table:

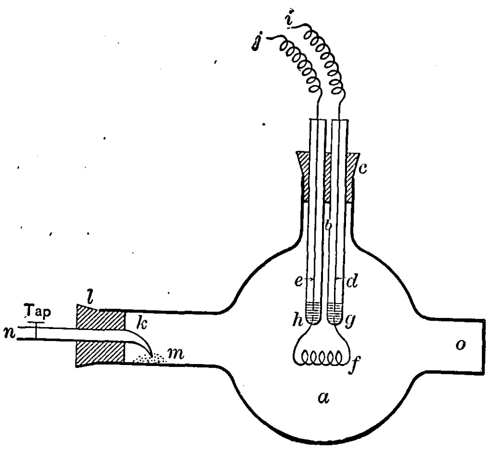


FIGURE 11.—Later coal-dust ignition apparatus of Bedson and Widdas.

Explosive character of coal dusts of stated composition as shown in experiments by Bedson and Widdas.

No. of experiment.	Nature of dust.	Composition of dust.						Pressure.[a]
		Moisture.	Volatile matter.	Fixed carbon.	Ash.	Ratio of fixed carbon to volatile matter.	Ratio of fixed carbon and ash to volatile matter.	
								Inches.
1	Artificial	14.86	45.77	35.87	3.50	0.78	0.81	....
2	.....do	1.52	34.01	58.55	0.94	1.50	1.51	5
3	.....do	6.08	38.22	52.85	2.85	1.38	1.46	5
4	.....do	8.58	31.89	57.78	1.81	1.81	1.86	2
5	Natural	1.07	27.49	63.72	7.72	2.32	2.59	4
6	.....do	5.20	29.05	42.22	23.60	1.45	2.27	1.5
7	.....do	5.01	28.38	37.08	29.60	1.30	2.35	1.5
8	.....do	6.00	21.70	7.63	64.67	.35	3.33	0
9	.....do	4.14	21.31	12.06	62.55	.56	3.50	0

1. Ground brown coal. 2. Ground coal from Hutton seam. 3. Ground coal from Grey seam coal. 4. Ground coal from yard seam coal. 5. Screen dust from Busty seam. 6. Dust from timber baulks and haulage roads in yard seam. 7. Dust from stone in roof of yard seam. 8. Dust from top and bottom of timber baulks and roof of Grey seam. 9. Dust from sides of haulage roads and pillar sides of Grey seam.

[a] The length of the sealed limb of the U tube above the level of the water in the tube is 12 inches. The pressure of 5 inches, therefore, would represent a compression sufficient to reduce the volume of air to seven-twelfths of its original volume, etc.

The authors in concluding their paper call attention to the influence which the proportion of volatile matter in the dusts exercises on their inflammability and explosive character, and assert that the method affords a ready means of judging the character of a coal with respect to these qualities. They express the hope of being able to contribute further results of a similar character.

In some of his work Bedson has made use of a different method for obtaining the relative pressures produced by the explosion of coal dust. This is a modification of the method used by Vital in his experiments.

EXPERIMENTS AT LIÉVIN, FRANCE.

A series of interesting experiments carried out in a comparatively small gallery at the Liévin station in France will next be considered. These experiments have been mentioned in another portion of this

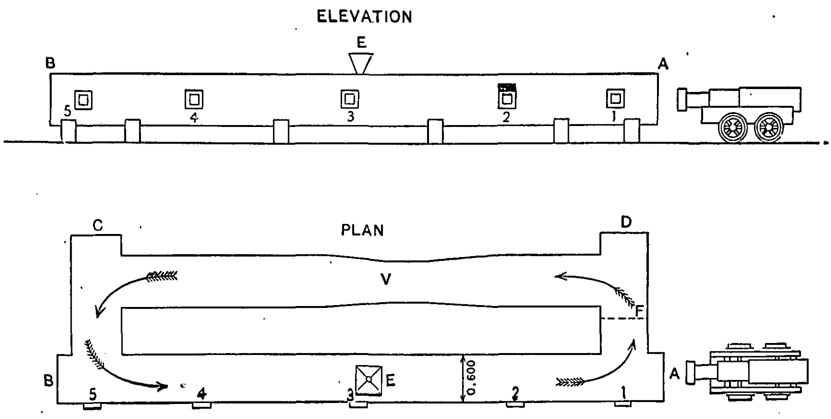


FIGURE 12. Coal-dust ignition apparatus used at Liévin.

bulletin (pp. 43–45) but they can scarcely be passed over here, because they embody the features of laboratory experiments together with those of actual mining conditions. They are, therefore, doubly interesting in this connection as bearing on both the quantitative side of the problem and its practical side. The experiments were performed in a small gallery (fig. 12), made of sheet-iron pipe, 0.6 meter in diameter, and arranged so as to form two galleries parallel to each other and connected at each end, so that the two galleries formed a closed circuit in which the air is made to circulate at regulated speed by means of a ventilator (V) placed near the middle of one of these galleries. The length of the gallery was about 7 meters. At the points A, B, C, and D were openings, which were closed during the experiment by means of paper diaphragms. The long side of the gallery A–B had five observation windows, numbered 1 to 5. Ignition was brought about by firing a cannon into the end

A or B, the muzzle of the cannon having first been placed against the diaphragm closing the end. In this way the ignition could be brought about either against or in the direction of the current of air in A–B. The shot was always fired with the ventilator in operation. The dust was introduced through E during the circulation of the current of air. The introduction was regulated by hand, so as to secure uniform distribution of the dust throughout the gallery. The time required to introduce the dust by hand was sufficient to permit the circulation of the air from five to fifty times around the closed circuit formed by the two galleries. The dust used throughout these experiments was passed through a 200-mesh sieve without any attempt to screen it to a certain size. The velocity of the air current used was from 4 to 5 meters a second, a velocity that was relied on as sufficient to maintain in suspension all of the dust of this degree of fineness. The total capacity of the apparatus was 4.5 cubic meters, and the density of the dust was determined by the amount introduced considering the whole amount as suspended at uniform density throughout the galleries.

When the cannon was fired into the gallery devoid of dust a rapid flame was seen at the first two windows, and at the same time all four paper diaphragms were ruptured. Identical results with a dust-laden air in the system indicated no inflammation. When inflammation occurred a red flame advanced at different velocities to various points of the gallery, or in some tests projected out the end opposite the cannon. Lacking the facilities for such work, the experimenters did not attempt to measure the velocity of propagation of the flame, but, judging by the eye, they were able to express the velocity as very slow, slow, or rapid. After each experiment the tubes were carefully cleaned.

In the course of this work eight different samples of dusts were examined. By varying the density of the dust, beginning with densities too low for inflammation to occur, they were able to arrange the dusts in the order of their inflammability under these conditions. The fact was brought out by this work that the order of inflammability is the same as that of the content of volatile matter in the coal. The same conclusion, as we have seen, was reached by other investigators, namely, Vital, Mallard and Le Chatelier, Holtzwart and Meyer, and Bedson and Widdas. Further factors considered by the author as determining the inflammability of dust are the character of the volatile matter and the percentage of ash in the coal; but the dusts as prepared for use in this investigation were of somewhat similar composition with respect to ash, so that the content of volatile matter was found to exercise a preponderating influence, and to determine the order of inflammability. Attention is also called to the influence which the ash exercises, both by increasing the weight of the particles, and by furnishing inert matter which must be heated up before inflammation occurs. The results, summed up in a table, have been given in an earlier part of this bulletin (p. 44). It is seen by inspection of this table, that of the eight dusts investigated, inflammation was obtained in all but the anthracite and Lens 2. The inflammability of the others was found to be greater according as they contained more volatile matter. The four types richest in volatile matter ignited at low densities, and the violence of the inflammation increased with the density of the cloud of dust. The point of greatest interest in connection with this work is the fact that inflammation and propagation of the flame throughout the available length of the gallery took place with a comparatively low density of dust, such as in mining conditions would be considered as indicating a comparatively dust-free gallery.

Since the publication of the preliminary bulletin containing the results of work done in the small gallery, further work has been done in this same gallery, and in one much larger. This work, however, is considered in another part of this bulletin (pp. 135–139).

In discussing the results of his work, Taffanel enters somewhat into the chemistry of dust explosions. No measurements of the pressure produced in the gallery, or of the velocity of propagation of the flame were obtained, because the necessary apparatus was lacking, but analyses of samples of gas taken from the gallery during the explosion have thrown much light on some of the problems involved.

Attempts to obtain samples of the gas after the explosion gave uncertain results because of the reentrance of fresh air. The method that was found satisfactory was to introduce into the gallery a closed glass tube, which communicated with an evacuated vessel outside of the gallery. By means of a detonator and instantaneous fuse, which was ignited by the passing flame, the closed glass tube was broken, and the evacuated vessel was filled with gas from the gallery in a fraction of a second. Analysis of this gas showed the presence of nitrogen, carbon monoxide, carbon dioxide, oxygen, and at times small quantities of methane. The distribution of the oxygen consumed between the carbon and hydrogen of the dust was obtained by deducting from the oxygen present in the beginning that consumed by the carbon plus that remaining free. The amount of carbon and hydrogen burnt per unit volume being known, and the amounts of the various constituents to be heated by this combustion, it was possible to calculate the theoretical temperature of the flame. This calculation gave a temperature ranging from 1,000° to 1,700° C.

The amount of carbon dioxide found, except when large amounts of dust were used, was much greater than the amount of carbon monoxide, and the absorption of heat, which takes place in the reduction of carbon dioxide to carbon monoxide, was not as great as had been expected. This is especially true in the flame itself, as the amount of carbon monoxide there is very small. It requires a certain amount of time to bring about the reduction of carbon dioxide, and the amount of carbon monoxide became appreciable only after elapse of such a period.

At first it was impossible to explain the part played by finely divided schist in retarding the propagation of the flame, as 100 grams of that material should lower the theoretical temperature only 50° C. Even after allowing for the absorption of heat that takes place when the chemically combined water of the schist is expelled, the calculated temperature was higher than the temperature in certain experiments in which propagation was obtained with coal dust alone.

The explanation given for this discrepancy is the difference in the screening action of coal dust and an inert dust. The effect of a dust cloud in front of the flame is to form a screen. With respect to coal dust, the greater the concentration the greater the surface of this screen per unit of volume, and the more favorable are the conditions for propagating the flame. But with a dust cloud composed partly of inert particles, these serve the same screening purpose, but do not take part in the combustion. They do not act like an excess of carbon, but merely by their screening effect they exercise a retarding influence in addition to that of the heat which they absorb in attaining the temperature of the flame.

By a careful interpretation of the analyses of gas taken during the explosions, it was demonstrated that certain particles of the coal were completely consumed, while others participated only to the extent of their volatile matter. For the propagation of the flame it is necessary that the proportion of substances undergoing rapid combustion—that is, the fine dusts and the distilled gas—should be somewhat more than enough to make the mixture inflammable, so that a sufficient amount of heat shall be disengaged to raise the dust cloud in front of the flame to the temperature of ignition. This may result from the volatile matter, or from the finest coal dust, or from a combination of the two. These, however, are complicated questions to be dealt with only by further experimental work.

FIRST SERIES OF EXPERIMENTS AT PITTSBURG TESTING STATION.

During the past year the writer has studied a number of coals with respect to their relative absorption of oxygen from oxidizing agents, especially standard solutions of chromic acid, with the thought that the amount of absorption would be indicative of the relative tendency of the different coals to take up oxygen from the air or to undergo spontaneous combustion.

In this connection it seemed desirable also to determine, if possible, the relative inflammability of some of these same coals, and quite recently, with this in view, a series of experiments was carried out on some of the same dusts used in studying the rate of oxidation. The apparatus used for this work is a modification of that of Bedson and Widdas described above.

Plate VIII, *A*, shows the form of apparatus used. *A* is an ordinary 2-liter aspirator bottle. *B* is a small filter flask of about 250 cubic centimeters capacity, connected at *a* by rubber tubing with *C*, a glass bulb of about 150 cubic centimeters capacity, and through the rubber stopper with the open manometer *c*. *D* is a glass tube 6.5 millimeters in internal diameter and 20 centimeters long, passing through holes in opposite sides of a box support, and set in firm and level position with plaster of Paris.

Through a rubber stopper in the mouth of *A* pass two large copper wires, which form the terminals for the platinum coil *d*. Through a hole in the same stopper passes a glass tube 13 millimeters in internal diameter, which is closed at the top, and to which is sealed a side tube (*e*) of the same diameter as *D*. This side tube is connected closely, end to end, with *D* by means of a short rubber tube. The platinum coil *d* is made from about 120 centimeters of No. 26 platinum wire, is suspended in two sections from a small perforated porcelain plate, and is connected with the copper terminals. The porous plate serves not only as a support for the coil but as a protection to the rubber stopper above from too high heating during the experiment, and also tends to disseminate the dust more uniformly in the upper part of the flask. The platinum coil when in position hangs slightly above the center of the bottle.

The tube *f* passing through the stopper in the tubulure at the bottom of the bottle is bent at a right angle and is made funnel-shaped at one end. The end carrying the funnel is directed upward inside the bottle toward the platinum coil, and directly under and within about 5 centimeters of it. In this funnel is placed the coal dust which it is desired to examine. The funnel and the fine wire gauze with which it is covered aid in securing a more complete dissemination of the dust when it is ejected from *f*. By means of a rubber tube *f* can be connected with *C*. Pinchcocks are at *g*, *h*, and *j*.

The terminals of the coil *d* are connected in series with an ammeter and rheostat. The relative pressure produced by the ignition of different dusts is measured by the distance to which a small steel ball (*b*) is projected, when this ball is placed at a definite point in *D* and in which it fits snugly.

Before each experiment the bottle *A* is thoroughly cleaned out and fresh air aspirated through it. Fresh air is also forced into *B* and *C* through *g* (pinchcock *h* being also open) until the desired pressure of mercury is indicated in the manometer *c*. The cock *h* is then closed and remains closed during the remainder of the experiment. The stopper carrying the coil is put in place, and the tubes *e* and *D* are connected. The tube *f*, containing the coal dust, is inserted in its proper place and connected with *C*.

To secure comparable results the coil is always heated the same length of time, three minutes, before the dust is scattered from *f*. The same current is used each time, and is kept perfectly constant the entire three minutes. With the coil used in these experiments a current of 6 to 7 amperes has been found satisfactory.

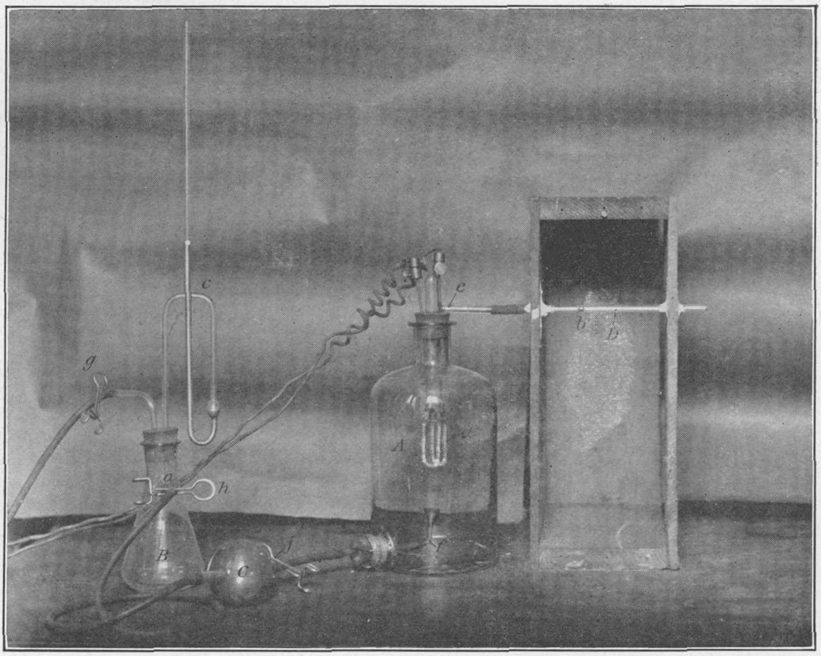
Just before scattering the dust the steel ball is placed exactly in position. At the end of the three minutes the cock *j* is released instantaneously, and the air entering *A* puffs the dust into the bottle and about the coil. It has been found better for the operator to replace the cock *j* and pinch the tube with his fingers before releasing, as the instantaneous release can be accomplished much more certainly in this way. The pressure in the bulb *C* of 150 cubic centimeters capacity being 165 millimeters of mercury, the pressure resulting therefrom in *A* would be only about 12.7 millimeters.

With the apparatus and method of procedure described above, the ignition of a number of coals has been studied. In every experiment ignition has taken place readily, except those with anthracite, natural coke, and charcoal.

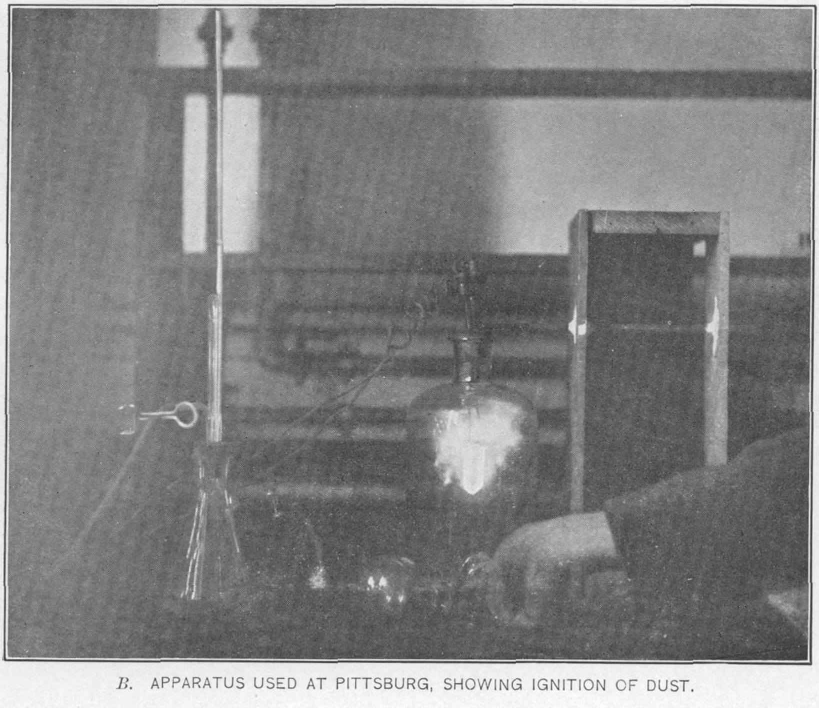
With a pressure in *C* of 165 millimeters of mercury, and a current of 6 to 7 amperes, 0.04 gram of dust was found quite sufficient for producing decided inflammation with all the coals investigated, with the exception already noted, and with some coals even less than this amount was required to produce measurable results.

In the table below are given the results of experiments with 11 coals of varying character and from different sources. In each experiment 0.04 gram of dust was used, dust meaning coal finely ground and passed through a 100-mesh sieve. The current employed was 6.4 amperes; the pressure in *C* was 165 millimeters of mercury.

In the first column of the table is given the character of the coal, while the third column shows, in centimeters from the end of the barrel *D*, the distance to which the metal ball was projected.



A. COAL-DUST IGNITION APPARATUS USED AT PITTSBURG.



B. APPARATUS USED AT PITTSBURG, SHOWING IGNITION OF DUST.

Results of laboratory experiments with explosive coal dusts at Pittsburg station.

Character of coal.	No. of experiment.	Distance ball was projected.	Character of coal.	No. of experiment.	Distance ball was projected.
		Cm.			*Cm.*
Pennsylvania bituminous	1	318	New Mexico bituminous	1	323
	2	325		2	312
	3	325		3	307
Illinois bituminous, noncoking	1	281	Kentucky cannel	1	317
	2	262		2	309
	3	284	Texas lignite	1	353
	4	277		2	339
Illinois bituminous gas coal	1	326	Dakota lignite	1	321
	2	335		2	293
Montana bituminous	1	306		3	295
	2	312		4	295
West Virginia bituminous	1	302		5	309
	2	320		6	319
	3	315	Colorado lignite	1	312
Alabama bituminous	1	323		2	363
	2	326		3	343

In the above tabulation no account is taken of the moisture or ash in the coals, nor of any deterioration of any of the samples that may have taken place before or after powdering and storing in bottles. As is shown in the table, lignites generally exhibited greater irregularity of results. The coals are not greatly differentiated here, probably because the heat supplied by the wire was too great in comparison with that supplied by the dust in burning, so that the differences of the dusts were masked.

The photograph reproduced in Plate VIII, *B*, was taken during one of the experiments. The flame observed has been in every test apparently confined to the upper half of the 2-liter bottle, as shown here. Consequently, the density of the mixture of dust and air at which the ignition occurred is not 0.04 gram of dust in 2 liters of air, but greater than that, 0.04 gram in less than 1 liter. Furthermore, the phenomena can not be considered as indicating indefinite propagation of the flame in an atmosphere containing the same density of dust, but only indicate propagation in the available space, and under the conditions of these experiments. It may be desirable to add that the inflammation was in all tests practically instantaneous and similar in appearance to the ignition of a slightly explosive gas mixture.

A great deal more work would have to be done before any positive statement could be made concerning the relative behavior of different coals. The same is true with respect to the effect of variations in the current used, and in the pressure with which the dust is brought into the bottle. A definite strength of current does, however, seem to be required for complete ignition, and beyond that strength variation of current has no effect. The initial pressure of the ignition mixture is probably of considerable importance.

An objection to the use of a platinum coil as a source of ignition is the possible catalytic action of the platinum.

It is hoped that further experiments can be performed on the ignition of coal dust by the use of pressure alone. It should be understood that the record given above is to be taken as a preliminary report of a few experiments performed under limited conditions, which are to a large extent repetitions of previous experiments, with some minor alterations of apparatus and method of manipulation.

SECOND SERIES OF EXPERIMENTS AT PITTSBURG TESTING STATION.

A second series of experiments is now in progress in which the pressures developed in the explosion vessel are measured by a different method. This method was adopted because the maximum pressure in many cases is not developed instantaneously, and the method previously used would on that account not give a true measure of the force of the explosion. The explosion vessel now in use is a 1,500-cubic centimeter glass globe with two tubulures on opposite sides. The dust is puffed into the vessel through the lower opening in much the same manner as in the experiments described above. Into the top opening is inserted a stopper carrying the same platinum coil used in the previous work. The measurement of the pressure is accomplished in the following way: A brass tube of 7 millimeters diameter is passed vertically through the rubber stopper which carries the connections of the platinum coil. (See Pl. VIII, *A*.) The top of this tube is ground so that a $\frac{5}{16}$-inch steel ball fits on it practically gastight. The pressure developed within the explosion vessel is measured by ascertaining by several trials the smallest weight which it is necessary to place on the steel ball to prevent it from being lifted from its position. In this way the total pressure exerted on a known area is obtained directly. The experiments have given quite concordant results, as can be seen from the table below:

Results of second series of experiments with explosive coal dusts at Pittsburg station.

[In all tests the amount of dust used was 0.04 gram.]

Source and proximate analysis of coal dust used and pressure developed in tests.	Results of tests.		
	Weight applied.	Equivalent per sq. cm.	Effect on steel ball.
	Grams.	*Grams.*	
1. Bituminous coking coal from Hastings mine, Las Animas County, Colo. (Lab. No. 9780):	300	779	Not lifted.
Moisture 1.43	275	714	Do.
Volatile matter 33.98	250	649	Do.
Fixed carbon 57.46	225	584	Do.
Ash 7.13	200	519	Do.
Sulphur .... .57	175	454	Do.
Pressure developed, less than 454 grams per square centimeter.			

Results of second series of experiments with explosive coal dusts at Pittsburg station—Cont'd.

Source and proximate analysis of coal dust used and pressure developed in tests.	Results of tests.		
	Weight applied.	Equivalent per sq. cm.	Effect on steel ball.
	Grams.	*Grams.*	
2. Bituminous free-burning domestic coal from Chandler mine,	250	649	Lifted.
Fremont County, Colo. (Lab. No. 9778):	260	675	Not lifted.
Moisture 6.49	255	662	Lifted.
Volatile matter 35.69	258	670	Not lifted.
Fixed carbon 52.25			
Ash 5.56			
Sulphur .... .49			
Pressure developed, 666 grams per square centimeter.			
3. Bituminous, noncoking steam or domestic coal, with cubical	250	649	Lifted.
or round fracture, from Maitland mine, Huerfano County,	270	701	Do.
Colo. (Lab. No. 9784):	272	706	Do.
Moisture 4.74	280	727	Do.
Volatile matter 38.24	285	740	Do.
Fixed carbon 49.32	290	753	Not lifted.
Ash 7.70	288	748	Lifted.
Sulphur .... .60	290	753	Not lifted.
Pressure developed, 751 grams per square centimeter.			
4. Noncoking, bituminous coal of "nigger head" or round forma-	275	714	Not lifted.
tion from Ravenwood mine, Huerfano County, Colo. (Lab.	260	675	Do.
No. 9781):	200	519	Do.
Moisture 3.49	150	390	Do.
Volatile matter 37.46			
Fixed carbon 49.62			
Ash 9.43			
Sulphur .... .99			
Pressure developed, less than 390 grams per square centimeter.			
5. Bituminous coking coal from Delagua mine, Las Animas	250	649	Not lifted.
County, Colo. (Lab. No. 9785):	250	649	Do.
Moisture 2.15	240	623	Lifted.
Volatile matter 34.45	245	636	Do.
Fixed carbon 53.42	250	649	Not lifted.
Ash 9.98	248	644	Lifted.
Sulphur .... .48			
Pressure developed, 647 grams per square centimeter.			
6. Bituminous coking coal from Bowen mine, Las Animas	250	649	Lifted.
County, Colo. (Lab. No. 9779):	270	701	Not lifted.
Moisture 1.44	260	675	Do.
Volatile matter 31.84	255	662	Do.
Fixed carbon 50.88	252	654	Do.
Ash 15.84			
Sulphur 3.21			
Pressure developed, 652 grams per square centimeter.			
7. Bituminous coking coal, high carbon, from Sun No. 2 mine,	250	649	Not lifted.
Fayette County, W. Va. (Lab. No. 9783):	230	597	Do.
Moisture 0.96	200	519	Do.
Volatile matter 21.08	150	390	Lifted.
Fixed carbon 73.38	160	415	Do.
Ash 4.58	170	441	Not lifted.
Sulphur .... .51	165	428	Do.
Pressure developed, 426 grams per square centimeter.	163	423	Lifted.
8. Bituminous coking coal from Ansted mine, Fayette County,	320	831	Not lifted.
W. Va. (Lab. No. 9787):	310	805	Do.
Moisture 1.83	305	792	Lifted.
Volatile matter 33.61	307	797	Do.
Fixed carbon 58.94	309	802	Not lifted.
Ash 5.62			
Sulphur .... .74			
Pressure developed, 800 grams per square centimeter.			

Results of second series of experiments with explosive coal dusts at Pittsburg station—Cont'd.

Source and proximate analysis of coal dust used and pressure developed in tests.	Results of tests.		
	Weight applied.	Equivalent per sq. cm.	Effect on steel ball.
	Grams.	*Grams.*	
9. Bituminous coal, coking, from Gem mine, Campbell County, Tenn. (Lab. No. 9782):	250	649	Not lifted.
Moisture 3.58	170	441	Do.
Volatile matter 34.18	140	363	Do.
Fixed carbon 54.98			
Ash 7.26			
Sulphur .... .74			
Pressure developed, less than 140 grams per square centimeter.			
10. Bituminous coal, steam and domestic, from Wooldridge mine, Campbell County, Tenn. (Lab. No. 9786):	250	649	Lifted.
Moisture 2.73	300	779	Do.
Volatile matter 35.85	320	831	Not lifted.
Fixed carbon 54.88	310	805	Lifted.
Ash 6.84	312	810	Not lifted.
Sulphur 1.07			
Pressure developed, 808 grams per square centimeter.			
11. Bituminous coking, high carbon coal from Jed mine, McDowell County, W. Va. (Lab. No. 10034):	250	649	Not lifted.
Moisture 1.01	100	259	Do.
Volatile matter 14.52			
Fixed carbon 77.65			
Ash 6.82			
Sulphur .... .71			
Pressure developed, less than 259 grams per square centimeter.			
12. Bituminous coking, high carbon coal from Elk Ridge mine, McDowell County, W. Va. (Lab. No. 10035):	250	649	Not lifted.
Moisture 0.97	100	259	Lifted.
Volatile matter 17.57	120	311	Not lifted.
Fixed carbon 77.65	110	286	Do.
Ash 3.81	105	272	Do.
Sulphur .... .58	102	265	Do.
Pressure developed, 262 grams per square centimeter.			
13. Bituminous, noncoking coal from Woodside mine, Sangamon County, Ill. (Lab. No. 9774):	250	649	Not lifted.
Moisture 13.13	225	584	Do.
Volatile matter 35.00	200	519	Lifted.
Fixed carbon 41.53	210	545	Do.
Ash 10.24	212	550	Not lifted.
Sulphur 3.48			
Pressure developed, 548 grams per square centimeter.			
14. Bituminous, noncoking coal from Little Vermilion mine, Vermilion County, Ill. (Lab. No. 10037):	250	649	Not lifted.
Moisture 13.92	150	390	Lifted.
Volatile matter 33.24	200	519	Do.
Fixed carbon 45.39	202	524	Not lifted.
Ash 7.45			
Sulphur 1.05			
Pressure developed, 522 grams per square centimeter.			
15. Subbituminous noncoking coal from Navajo mine, N. Mex. (Lab. No. 10038):	200	519	Lifted.
Moisture 12.65	230	596	Do.
Volatile matter 39.57	250	649	Do.
Fixed carbon 37.67	260	675	Do.
Ash 10.11	280	727	Do.
Sulphur .... .47	285	740	Not lifted.
Pressure developed, 730 grams per square centimeter.	282	732	Do.

Results of second series of experiments with explosive coal dusts at Pittsburg station—Cont'd.

Source and proximate analysis of coal dust used and pressure developed in tests.	Results of tests.		
	Weight applied.	Equivalent per sq. cm.	Effect on steel ball.
	Grams.	*Grams.*	
16. Subbituminous, noncoking coal from Weaver mine, N. Mex.	282	732	Not lifted.
(Lab. No. 10039):	230	597	Lifted.
Moisture........ 12.14	240	623	Not lifted.
Volatile matter........ 38.82	235	610	Do.
Fixed carbon........ 37.78	232	602	Do.
Ash........ 11.26			
Sulphur........ .52			
Pressure developed, 606 grams per square centimeter.			
17. Subbituminous, noncoking coal from Superior mine, Wyo.	200	519	Lifted.
(Lab. No. 10040):	225	584	Do.
Moisture........ 10.45	250	649	Do.
Volatile matter........ 38.28	260	675	Do.
Fixed carbon........ 45.06	270	701	Do.
Ash........ 6.21	280	727	Not lifted.
Sulphur........ .85	275	714	Lifted.
Pressure developed, 718 grams per square centimeter.	278	722	Not lifted.
18. Subbituminous, noncoking coal from Superior mine, Wyo.	250	649	Lifted.
(Lab. No. 10041):	300	779	Not lifted.
Moisture........ 5.17	275	714	Lifted.
Volatile matter........ 40.23	290	753	Do.
Fixed carbon........ 52.77	295	766	Do.
Ash........ 1.83	300	779	Not lifted.
Sulphur........ .68	297	771	Do.
Pressure developed, 769 grams per square centimeter.			
19. Subbituminous, noncoking coal from Weaver mine, N. Mex.	278	722	Lifted.
(Lab. No. 10042):	300	779	Do.
Moisture........ 12.81	305	792	Not lifted.
Volatile matter........ 38.83	302	784	Lifted.
Fixed carbon........ 43.06			
Ash........ 5.30			
Sulphur........ .59			
Pressure developed, 782 grams per square centimeter.			

The experiments recorded in the table were made on equal weights of the dusts, and each sample was ground to pass through a 100-mesh sieve. These results are interesting chiefly for two reasons. First, they show what degree of accuracy may be expected from this method of examining the explosive character of dusts. From experience it may be stated that the pressures developed in almost all of the tests could be measured to about 1 per cent of the total pressure developed. Second, the results are of most importance in showing the care which must be taken in preparing the dusts in order that the results obtained with different coals may be strictly comparable. Each sample of coal was ground in a ball mill, so that the whole of the sample passed through a 100-mesh sieve, and efforts were made to have them ground as nearly as possible to the same degree of fineness. But this object was not attained by any means. It was shown that fully 90 per cent of those dusts which developed the greatest pressures in the explosion vessel would pass through a 200-mesh sieve, whereas of some samples only about 30 per cent would pass through the same sieve. To obtain comparable results it will be necessary to impart to all of a sample such a degree of fineness that the whole amount introduced into the explosion vessel will take part in the explosion. A series of experiments is being conducted on the same coals that were used in the tests described above. The samples used in this series were ground so that the whole passed through a 200-mesh sieve. The following results of experiments are given for comparison of the pressures developed in the previous experiments with the pressure developed by the same samples ground to pass through a 200-mesh sieve.

Comparison of pressures developed by 100-mesh and 200-mesh coal dusts of like composition.

		Grams per sq. cm.
Coal No. 9780	100-mesh	Less than 454
	200-mesh	549
Coal No. 9778	100-mesh	666
	200-mesh	703
Coal No. 9784	100-mesh	751
	200-mesh	774
Coal No. 9781	100-mesh	Less than 390
	200-mesh	626
Coal No. 9785	100-mesh	647
	200-mesh	667

If it is not possible to obtain dust sufficiently finely divided to get comparable results it will be necessary to screen the samples used for the tests with more than one sieve and to use in each test only dust whose particles are between certain sizes. This process may change somewhat the composition of the dust from that of the original coal and will not be used except as a last resort.

SIGNIFICANT POINTS IN EXPERIMENTS.

In closing this short summary of the laboratory experiments on the ignition of coal dust, it may be well to call attention to certain facts which they show. In the first place, the phenomenon of ignition is very complex, and for that reason it is necessary to have the proper conditions in order to demonstrate the ignition of coal dust on a laboratory scale. It has been pretty well demonstrated by these experiments that the order of inflammability of a coal dust is a function of the amount and character of the volatile matter which is expelled, the ease with which it is given up, the fineness of division of the dust particles, the density of the cloud, the character of the source of ignition, the amount of water and ash, and, finally, the pressure prevailing in the neighborhood of the flame. It does not seem that sufficient attention has been given to the last condition. Several facts brought out in the experiments support this statement.

Unless there is an exceptionally large amount of dust in the air, experience shows that ignition does not take place from a naked flame.

This fact is illustrated by the work of Galloway, and that of Mallard and Le Chatelier (who used for the source of ignition different kinds of naked flames, and accords with the conclusions which they reached as a result of their work. It will be recalled, too, that Holtzwart and Meyer drew attention to the fact that no ignition was obtained if they introduced lignite dust into their apparatus, and, after establishing the spark between the terminals within, disseminated the dust in the air by shaking the tube. But when the dust was puffed between the terminals by compressed air ignition occurred. Dust explosions in mines and in successful experiments in galleries specially designed for these investigations are preceded by violent compressions simultaneously with the production of a large flaming area by the charge of explosive (the means of ignition always used). Attempts will be made to ascertain the effect of pressure alone on coal dust suspended in air and in some inert gas.

COAL-DUST INVESTIGATIONS AT EUROPEAN TESTING STATIONS.

By Axel Larsen.

PROTECTIVE MEASURES UNDER STUDY.

The investigation of coal-dust explosions is naturally divided by two purposes: (1) Demonstration of the inflammability of coal dust, and (2) determination of the best means of preventing or arresting explosions. Inflammability may now be regarded as demonstrated. The second purpose, however, is likely to involve further experiments on a still larger scale than at Altofts in England and Liévin in France. Systematic scientific study of all phenomena and conditions bearing upon the combustion of coal dust, from the moment of its ignition through all subsequent stages of propagation until the highest point of velocity, approaching true detonation, is reached, has been generally recognized as an indispensable guide to gallery experiments; but it is felt that even the largest existing galleries are not long enough to admit of definite conclusions regarding the preventive measures to be adopted in actual practice.

Foremost among such measures are the so-called protection zones. Of these, three kinds have been experimented with, namely: Dustless, watered, and stone-dust zones.

The stopping power of dustless zones has proved comparatively slight, especially where the explosion has traveled a long distance and developed both high velocity and a dense "vanguard" cloud. Besides, it is not easy to remove coal dust completely and prevent its reaccumulation, even on comparatively short lengths of roadway in a mine.

Watered zones are probably more effective provided the watering is sufficient. But such sufficiency appears to depend greatly on local conditions and on the character of the dust to be dealt with. In German mines, more particularly in the Westphalian and Saarbrücken coal fields, systematic watering has been made compulsory by law, and in spite of the numerous drawbacks attending its installation and upkeep, both owners and men have accepted the measure with growing favor. In Belgium, on the contrary, extensive watering has been considered impractical, owing to the damage said to be caused to walls and roof. The same is true in many English mines, although in Wales the watering system is extensively practiced.

Stone dust has in the experimental galleries so far given the best results, and its use entails but few of the disadvantages of the two other methods. Its efficacy as a stopping agent has been experimentally demonstrated both in England and in France, although the results are not entirely concordant. The dissimilarity, for instance, between the results in the tests depicted in figure 13 is remarkable, considering that the two galleries are practically alike and that the conditions of the tests are apparently analogous.

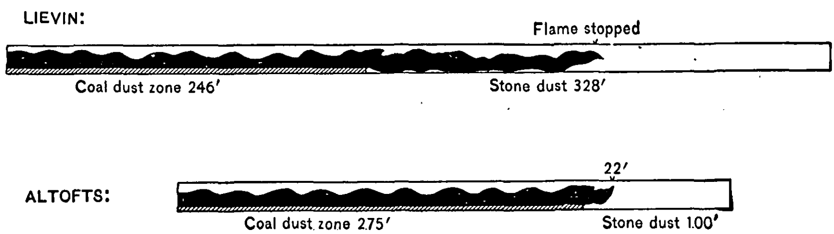
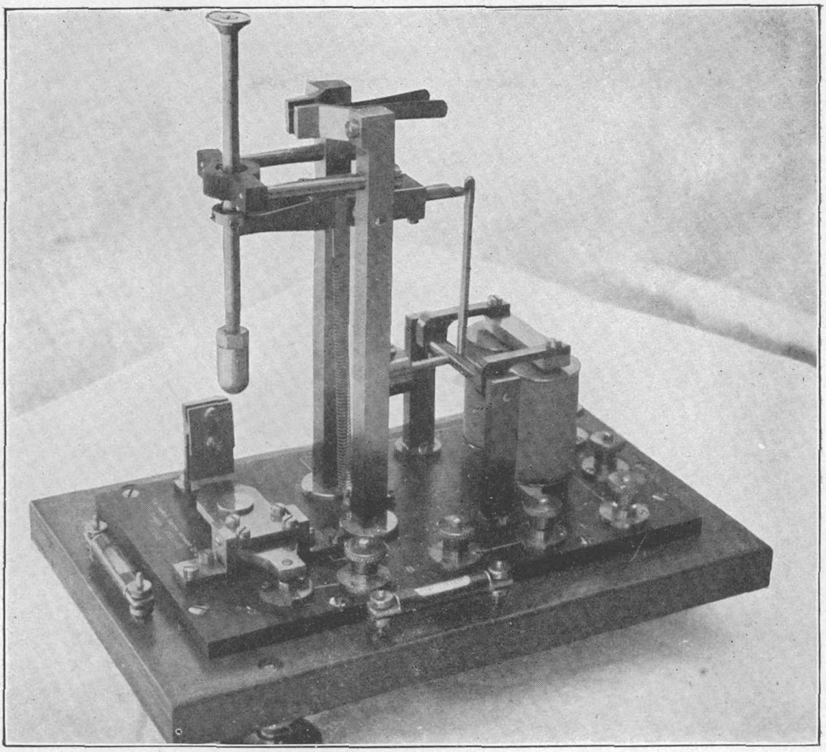


FIGURE 13.—Relative effect on flame of stone-dust zones at Liévin and at Altofts.

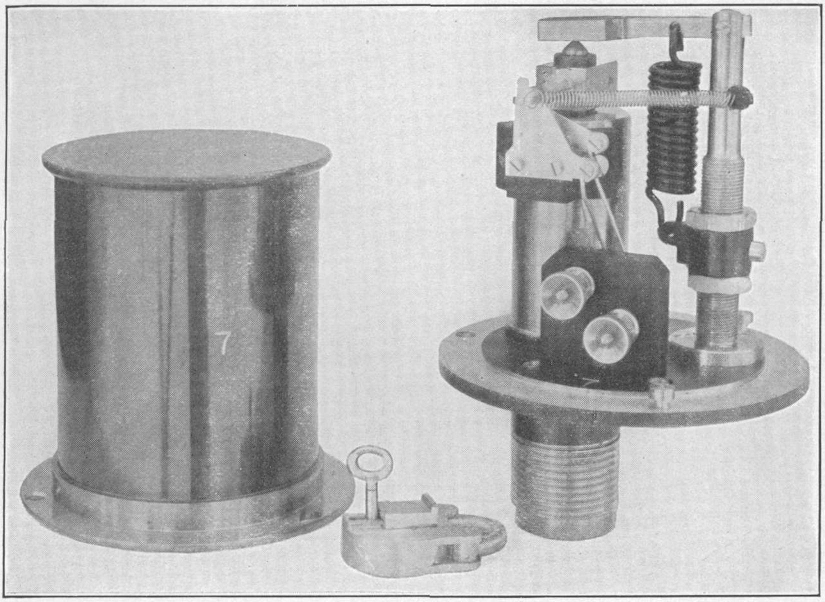
Such, at least, is the impression received at the first glance. But it is, of course, quite possible that the numerous factors influencing an explosion may produce apparently discrepant results by acting in different order in different tests, and that when properly understood and accounted for such results may yet be brought into harmony. Indeed, if this were not credible, all attempts to determine adequate lengths of protection zones in mines by extrapolation would appear futile.

At the time of writing this report no information could be obtained at either station as to any existing ratio of increase between varying lengths of coal dust and stone dust. But as the recording instruments at Altofts have shown that the pressure increases but slowly over a distance of 200 to 300 feet, and then suddenly rises to the maximum, it may be assumed that if a coal-dust zone of, say, 600 feet were employed for originating and propagating an explosion, the pressures obtained in an adjacent stone-dust zone would be very different from those obtained by shorter lengths of the propagating zone. Hence the employment of the relatively short propagating zones at

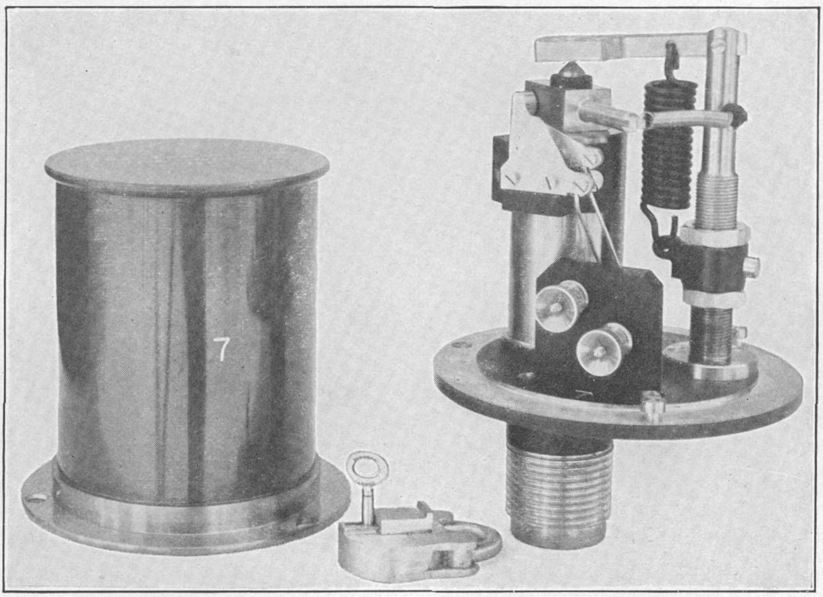


A. TIME MARKER, ALTOFTS EXPERIMENTAL GALLERY.

B. MANOMETER, ALTOFTS EXPERIMENTAL GALLERY.



A. CONTACT BREAKER, ALTOFTS EXPERIMENTAL GALLERY; BEFORE FIRING.



B. CONTACT BREAKER, ALTOFTS EXPERIMENTAL GALLERY; AFTER FIRING.

the Altofts gallery, which, owing to the limitation of strength of the gallery tube, have to be confined to about 367 feet, is inadequate for complete solution of the problem.

APPARATUS AND METHODS AT ALTOFTS AND LIÉVIN.

GENERAL STATEMENT.

The complex study of coal-dust explosions obviously involves the use of delicate recording instruments. Both at Altofts and at Liévin the equipment in this respect, most of which has been specially designed, apparently leaves little to be desired.

At stations where observations have not yet been sufficiently extended, the selection of instruments will now be greatly facilitated by experience gained elsewhere. It is gratifying to acknowledge that the benefit of such experience is freely and willingly offered to all interested, both at Altofts and at Liévin.

INSTRUMENTS AT ALTOFTS.[a]

Measurement of pressure.—The B. C. D.[b] manometer (Pl. IX, *B*) records the movement of a strong spring under the pressure of a coal-dust explosion. In order to reduce error caused by the inertia of the moving parts they are made as light as possible and the amount of movement of the spring is as small as is convenient for accurate measurement. The spring itself is triangular in form and clamped at its base, the force acting vertically upward at its apex. With this form the maximum strain is the same at all cross sections of the spring and the inertia is also reduced, because the narrow lighter part of the spring moves most and the wide heavier part least.

The pressure acts directly upon a surface of oil contained in a hexagonal oil box and is transmitted to a light hollow cylindrical plunger (closed at the bottom) moving in the oil box through a hole in the top. This arrangement keeps the plunger well lubricated, reduces leakage past it, and prevents the fine dust with which the gas is charged from cutting and clogging the rubbing surfaces. It also damps out any rapid vibrations due to sudden shock.

The natural period of vibration of the spring is one one-hundred-and-fiftieth of a second, and such vibrations do not mask the actual fluctuations of pressure due to the explosion. The plunger makes contact with the spring by means of a loose link, one end of which rests in a conical depression in the bottom of the plunger and the other in a similar depression in the face of the spring.

[a] The writer is indebted to Mr. W. E. Garforth and Doctor Wheeler for the accompanying photographs and the following descriptions of instruments used at Altofts.

[b] B. C. D., the distinguishing mark used for these instruments by the makers, stands for "British coal dust."

The spring carries a fine scribing point which rests lightly against a smoked surface of paper fastened on a heavy drum which can be made to revolve by means of an electric motor; a continued record of the development of pressure is thus obtained.

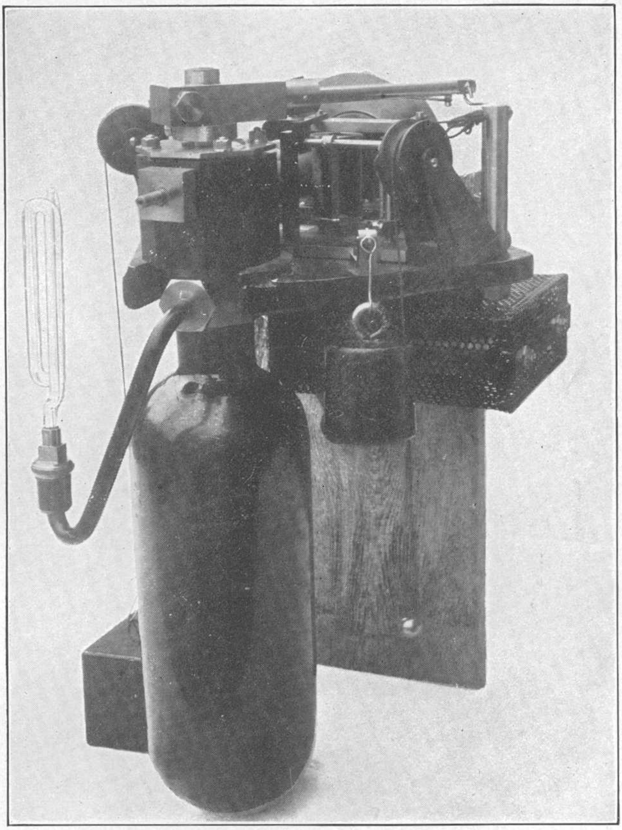
The speed of revolution of the drum is obtained by a special $\frac{1}{10}$-second time marker (Pl. IX, *A*). An accurate standard of time is obtained by measuring the time that a weight takes to fall from rest through a measured distance; this distance is so arranged that the time interval shall be exactly one-tenth second. A break in the electric circuit occurs at the begininng and at the end of the fall of the weight, and these breaks are recorded on the surface of the smoked paper on the manometer drum by the movement of a light style attached to an electro-magnet.

Measurement of velocity.—In order to record the speed of passage of pressure along the experimental gallery, contact breakers are screwed into the top 50 feet apart. They consist of light plungers, which can be weighted at will to withstand from 2 to 20 pounds initial pressure per square inch, and which on the slightest movement upward break an electric circuit. Plate X, *A*, shows the position before firing and Plate X, *B*, that after firing. The breaks in electric current are recorded by means of a standard chronograph. In order to be able to record a large number of breaks (as many as 12 have been used), and to avoid the error caused by differences in the latency or "lag" of the electro-magnets on the chronograph, a special automatic commutator has been devised which enables all the breaks to be registered by one electro-magnet. An escapement wheel carrying the commutator brush tends to be pulled round over the stops, but is held back by an anchor escapement attached to the armature of an electro-magnet. The circuits from the contact breakers on the gallery are connected through this commutator before passing to the chronograph. One lead of each circuit passes to the electro-magnet terminal and the other leads are connected, in order, to the numbered terminals of the stops of the commutator.

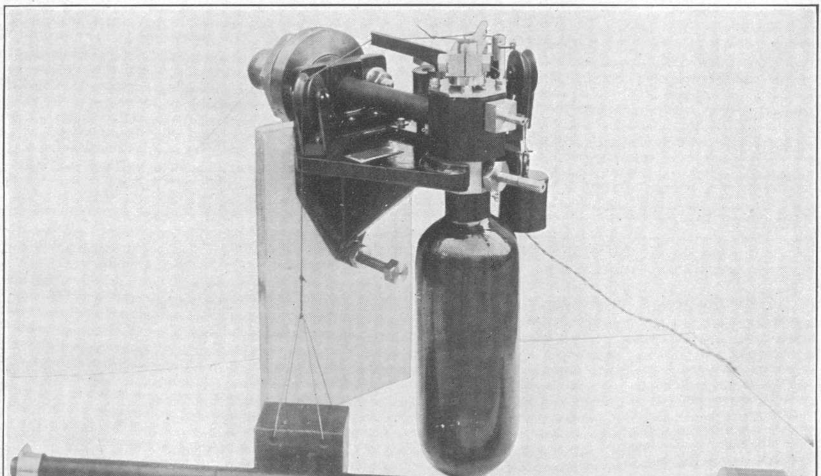
The value of this instrument depends upon the time that the brush takes to pass between two successive steps. This has been reduced to less than one-sixtieth second, so that, if the contact breakers on the gallery are 50 feet apart, velocities as high as 3,000 feet a second can be determined.

Sampling of after-damp.—The B. C. D. sampler (Pl. XI, *A* and *B*) consists essentially of an exhausted bottle which can be opened to the explosion gallery at a known time and closed at will after a short interval; these conditions are essential for a correct interpretation of the results obtained.

A pipe passes through the side of the gallery 2 feet into the interior. It is closed at the inner end by a small glass bulb fastened in by

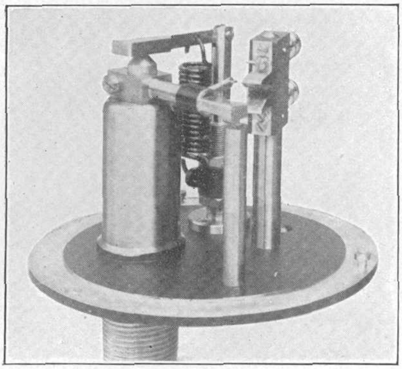


A.

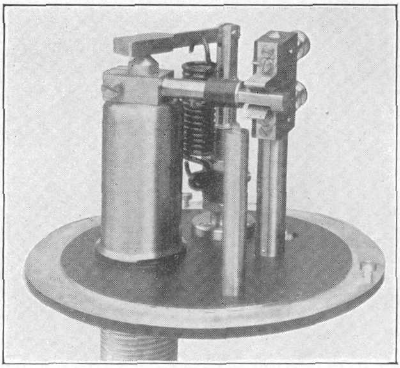


B.

AFTER-DAMP SAMPLER, ALTOFTS EXPERIMENTAL GALLERY.

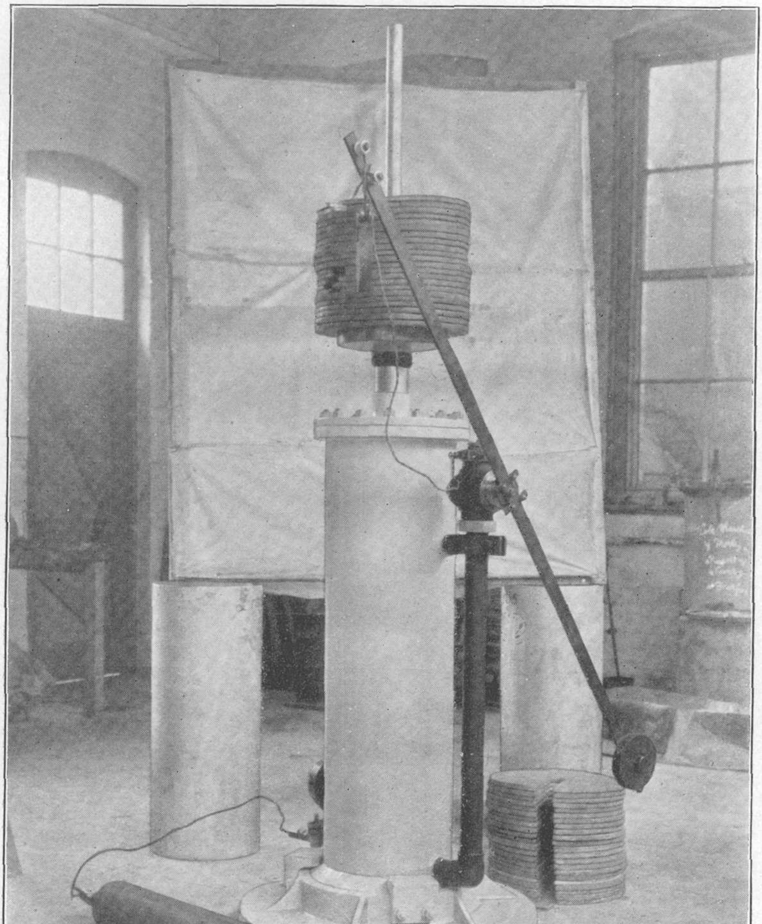


A. Before firing.



B. After firing.

CONTACT MAKER USED AT ALTOFTS EXPERIMENTAL GALLERY.



C. APPARATUS FOR IGNITING COAL DUST BY GAS FLAME, ALTOFTS EXPERIMENTAL GALLERY.

Opened by detachment of lever weight.

sealing wax. The outer end of the pipe is screwed to the sampling bottle and the whole then evacuated. A small hammer head is fixed just over the glass end, held back by a fuse wire. On the fusing of this wire the hammer falls and breaks the glass, thus allowing the gases to enter the exhausted bottle. The same current that fuses the wire also releases a small weight, which, after falling a certain distance, pulls out a pin, thus allowing a heavy weight to fall and in falling to close a tap at the head of the bottle. The gases are afterwards withdrawn through a mercury pump for analysis. The time that the bottle remains open depends upon the distance that the small weight falls; this can be varied at will.

The time at which the bottle is opened to the gallery by the breaking of the glass bulb is determined by causing the explosion itself to make the electric current pass through the fuse wire; this is effected by means of the B. C. D. contact maker shown in Plate XII, *A* (before firing), and *B* (after firing).

CALCULATION OF TEMPERATURE AT ALTOFTS.

The temperature of explosion (T) is calculated at Altofts from the pressure on the assumption that T=Z+pt; Z being the original temperature (absolute) of the gases, p the observed pressure, and t the normal temperature. For example:

Let $p=10$ atmospheres;
$t=10°$ C. and therefore
$Z=10°+273°=283°$ C.
Then $T=283+2,830=3,113°$ C.

CHANGES IN GALLERY AT LIÉVIN.

At Liévin station an important change has been made since last summer in the construction of the intake portion of the principal gallery. This was trapezoidal in section, buried under stone débris, and constructed so as to permit different kinds of timbering, the idea being to imitate, as far as possible the structural features of a roadway in the mine.

The violent dislocations of timber frames, however, and other heavy damage caused by the force of explosions, necessitated a stronger construction, and the whole of the buried part of the gallery (38 meters) has been replaced by boiler shells 10 millimeters in thickness and 2 meters in diameter. The gallery is lined with wooden boards and ballasted outside with débris so as to leave the top free. (See fig. 14.)

The gallery, which was 230 meters long in October, will be extended to a total length of 400, perhaps 500 meters.

INSTRUMENTS AT LIÉVIN.

Measurement of pressures.—The recording instruments for measuring pressures at Liévin comprise: (1) Spiral spring gages graduated to indicate $\frac{1}{2}$, 2, and 5 kilogram pressures per square centimeter; (2) copper-disk crusher gages of known pattern; and (3) "Thomson's tubes," as used for taking deep soundings. The last consist of thin glass tubes about 20 inches long, open at one end and filled with chromate of silver. When placed in an iron tube containing salt

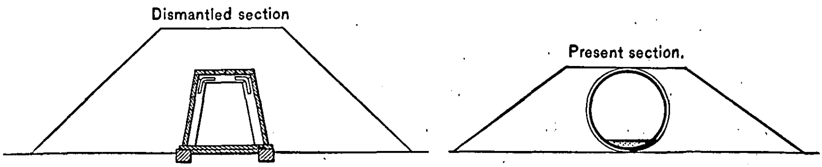


FIGURE 14.—Dismantled and present sections of Liévin gallery.

water and inserted into the gallery, the pressure causes the water to mount into the glass tubes, discoloring the chromate. Although the pressure records obtained in this manner are not invariably trustworthy, the method is inexpensive.

Measurement of rate of propagation.—The rate of propagation of flame is obtained by means of a number of electric circuits which are broken by the passing flame. The interruptions of current are recorded on a chronograph. The connecting wires enter the gallery at regular intervals through iron tubes fixed under the roof, as shown in figure 15. The circuit is broken at the point marked x through the explosion of a fulminating cap.

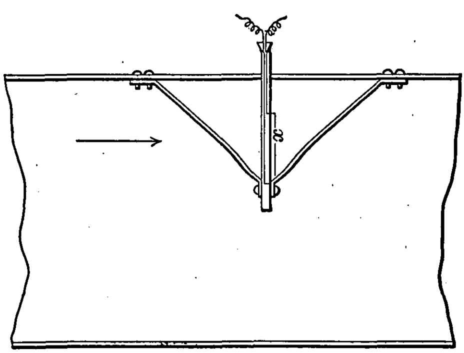


FIGURE 15.—Device for breaking circuit in explosion gallery at Liévin.

Measurement of temperature.—For measuring the temperature of explosion a thermocouple and a Le Chatelier galvanometer have been used, but for very violent and rapid explosions they are not satisfactory.

Taking samples.—The contrivance used at Liévin for taking samples of the combustion gases is a simplified adaptation of the more elaborate instrument at Altofts, and consists of an evacuated glass retort ending in a long-drawn closed bent tube at the end of which a detonator is fixed. The flame fires the detonator and the gases rush into the glass vessel. By filing an indention into the glass tube at a suitable distance above the detonator the tube is made to break at that point and the entrance of fulminate combustion gases is thus supposed to be obviated.

RESULTS AT ALTOFTS AND LIÉVIN.

EXPERIMENTS WITH PROTECTION ZONES AT LIÉVIN.

The following is a synopsis of results obtained at the Liévin gallery with zones of protection against coal dust:

The gallery was divided into three zones, a, b, and c, 75, 100, and 60 meters long, respectively.

To test the effect of a watered zone of coal dust, zone a was lined with fine Liévin coal dust, containing 30 per cent volatile matter; b with watered coal dust (2 liters per meter); and c with coarse coal dust. The result was slow propagation of the flame, visible 60 meters outside of the gallery.

In a second test a contained coal dust as before; b was dustless, but watered as before; and c contained coal dust as before. The flame stopped midway of zone b.

To test the effect of stone dust, in a was placed 450 grams of coal dust per cubic meter, in b 450 grams per cubic meter of pure stone dust, and in c 900 grams of coal dust per cubic meter. As a result the stone-dust zone stopped the flame about midway. If the stone dust strewn in zone b is reduced to 225 grams per cubic meter, however, the flame leaps over to c.

In another test of stone dust a and c were arranged as before, while b contained a mixture (450 grams per cubic meter) consisting of 25 per cent coal dust and 75 per cent stone dust containing carbonate of lime. As a result the flame leaped across zone b.

REPORT OF WORK AT LIÉVIN.

In a few months M. Taffanel expects to publish a full account of the coal-dust experiments and recent research work carried out at Liévin station.

CONDITIONS AT ALTOFTS.

At the Altofts station, work in the gallery is discontinued during the winter months. The foggy weather which generally prevails during that part of the year obviously produces different working conditions, which render uniform results difficult and frequently impossible. Moreover, the gallery is closely situated to three railroad lines, and though a system of signaling has been agreed upon with a view to the safety of passing trains, any serious dislocation of the railroad traffic in foggy weather would practically compel the suspension of gallery work.

During such periods of adjournment the steadily accumulating laboratory work and questions of equipment are attended to. As already mentioned, the station now possesses a set of the finest instruments yet produced for this particular work.

The file of boilers originally placed in line has been shortened so as to leave an intake gallery of 600 feet only.

The number of experiments carried out to date amounts to 115, about half of which have been "spectacular," that is, repetitions of phenomena regarding which those in charge were long ago satisfied, but which it was considered necessary, or at least desirable, to repeat in order to convince stanch unbelievers in coal-dust explosions.

EXPERIMENTS WITH PROTECTION ZONES AT ALTOFTS.

Apart from the crucial demonstrations of true coal-dust explosions furnished there during two seasons, much attention has been given

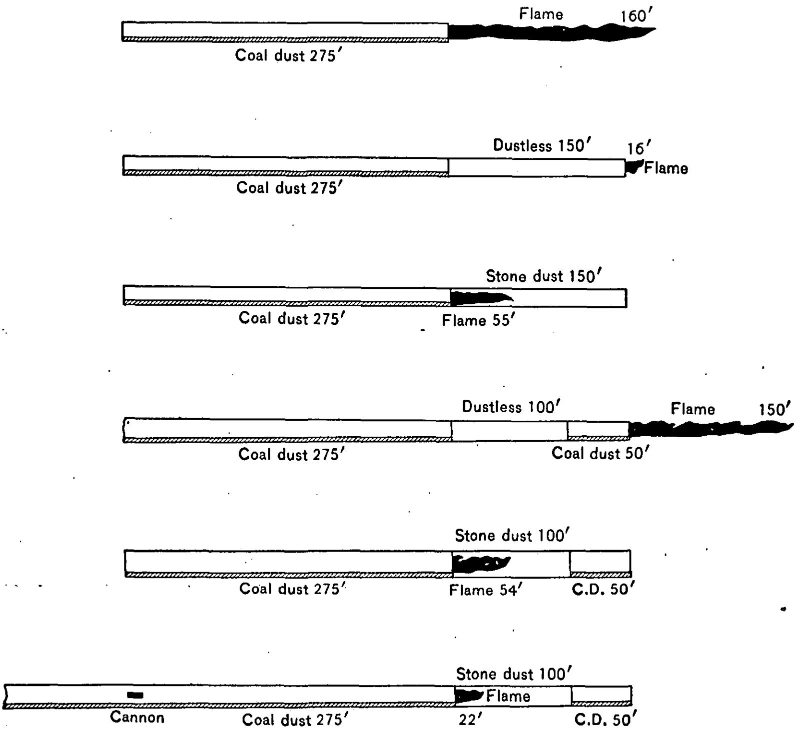
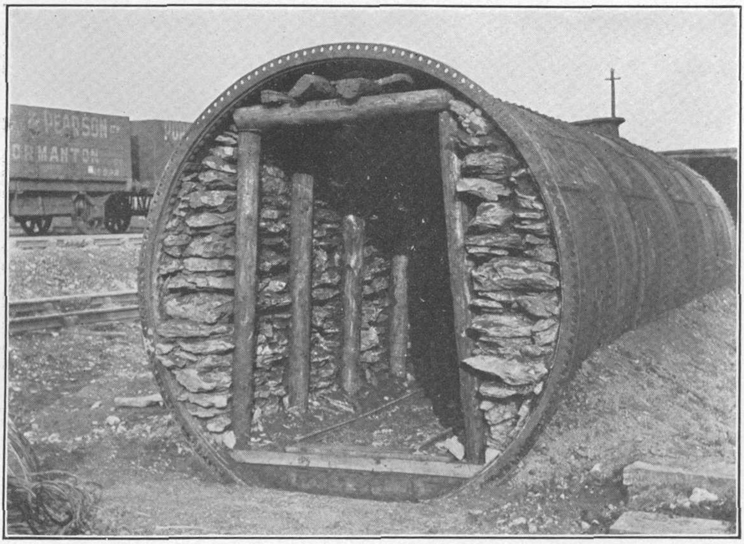


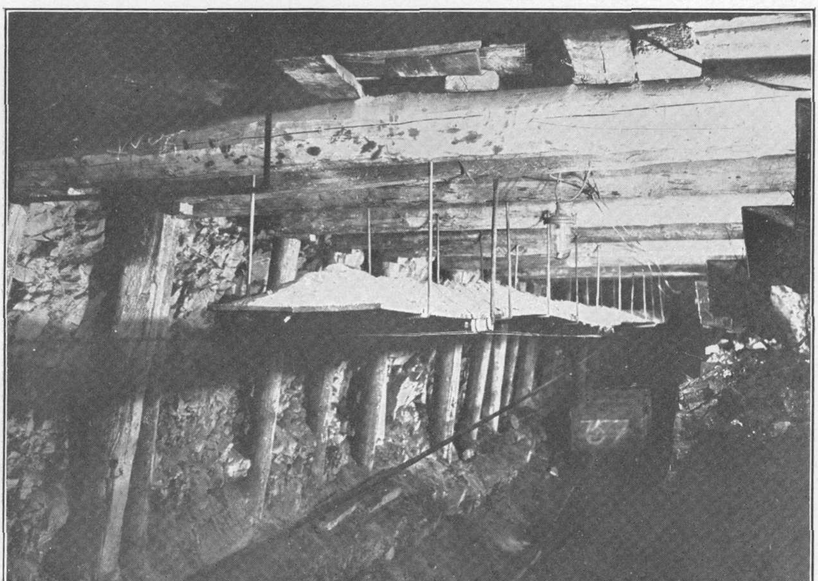
FIGURE 16.—Propagation of flame in coal-dust, dustless, and stone-dust zones.

to the question of the relative protection afforded by dustless and stone-dust zones. Stone dust has been found to be the most effective. The results of experiments typical of that particular investigation are shown in figure 16.

Instructive as these tests undoubtedly are, they can at best serve as a stimulus for gaining further knowledge, and must not be regarded as exhaustive; nor will they help to discover what would happen should the length of the coal-dust zone be doubled, or even trebled. This can only be determined by future experiments on a still larger scale.



A. TIMBERING AND STONE PACKING IN ALTOFTS GALLERY.



B. STONE DUST ON HANGING SHELVES IN ALTOFTS COLLIERY.

By means of the present equipment, however, it has been possible to show that when once initiated in the presence of abundant and inflammatory sustenance a coal-dust explosion will travel comparatively slowly for a hundred yards, when suddenly a high temperature will develop, accompanied by corresponding concomitant pressures. If, after this, conditions still remain favorable to propagation, the maximum pressures and velocities will probably prevail undiminished until opposed by tracts of nonsupporting or screening material.

EXPERIMENTS AT ALTOFTS ON MEANS OF IGNITION.

In reference to the initiation of a coal-dust explosion it may here be mentioned that although shot firing has hitherto been resorted to in the galleries, the fact that a blown-out shot is but one of several possible causes in practice has at last been recognized, and consequently other means of ignition are about to be attempted. When the writer visited Altofts he had an opportunity to see an apparatus designed to produce a long gas flame of sufficient volume and duration to ignite coal dust in suspension without setting up high pressures such as are caused by explosives (Pl. XII, *C*).

It consists of a cylinder which is filled with gas. At the end of the outlet tube there is a specially constructed valve operated by a long turning bar carrying a weight at each end. One of the weights is suspended by means of a piece of wire which forms part of an electric circuit with a current of sufficient tension to fuse it. When the weight is released in this manner, the other weight causes the bar to revolve and thus to open the outlet valve. A heavily weighted piston drops to the bottom of the gas cylinder, causing the gas to rush out at an adjustable pressure. The gas is simultaneously ignited by an electric spark inside the gallery. Figure 17 is a rough sketch of the apparatus.

DISTRIBUTION OF STONE DUST IN ALTOFTS GALLERY AND MINE.

In the majority of coal-dust experiments carried out at Altofts props and tubs have been placed in the gallery and even stone packing has been built in behind the timbering (Pl. XIII, *A*).

Hanging shelves carrying an extra supply of stone dust, as used in the Altofts mine, were likewise provided along the stone-dust zones (Pl. XIII, *B*).

Through the courtesy of Mr. Garforth, chairman of the Altofts Colliery Company, the writer was given the opportunity of inspecting the distribution of stone dust in the mine. The dust is thrown onto the walls of the roadways by hand, the greater part of the coal dust adhering to them being displaced by the process. Stone dust is also strewn on the floor. It was stated that every district in the mine was isolated by stone-dust zones 600 feet in length. The dust required but occasional renewal, and its application gave little or no trouble. The cost was said to be about 1 penny (2 cents) per linear yard of roadway with a section of 10 by 7 feet, exclusive of cost of crushing and grinding.

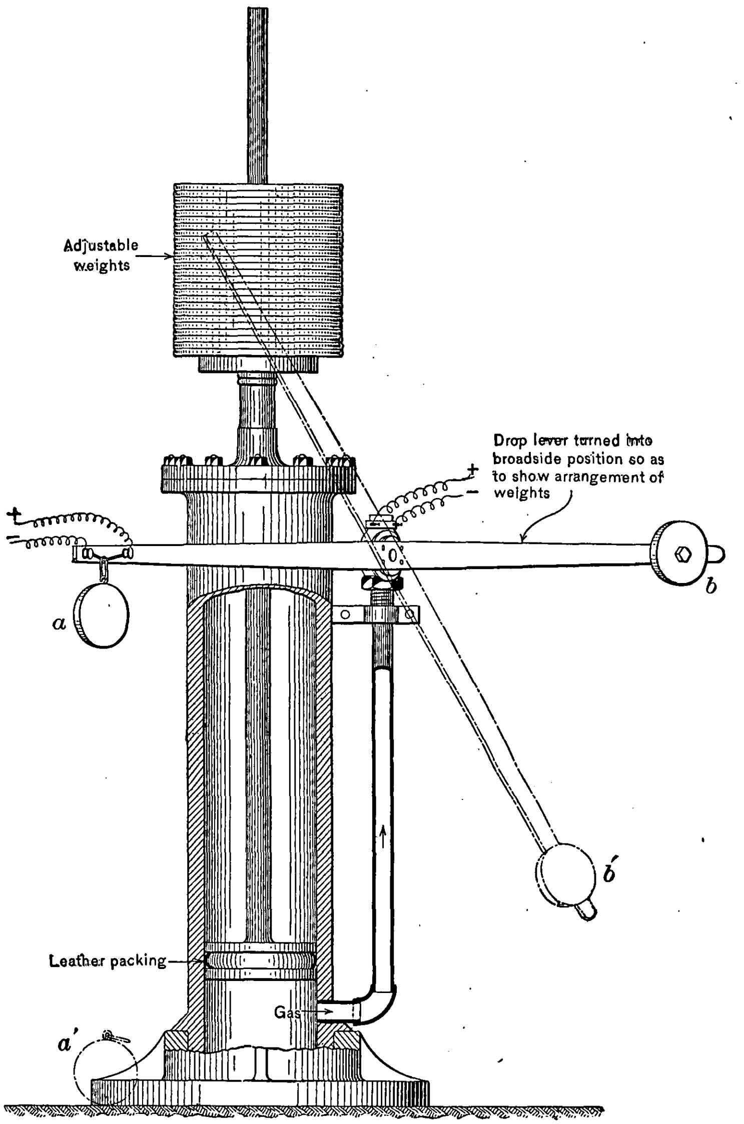


FIGURE 17.—Elevation of apparatus for igniting coal dust by gas flame.

FUTURE WORK AT ALTOFTS.

Experiments at the Altofts gallery will be resumed in May, 1910. Meanwhile a full report on the work done to date is being prepared and will be published shortly.

INVESTIGATIONS AT FRAMERIES IN BELGIUM.

DIRECTION OF INQUIRY.

In Belgium investigations on coal dust have been chiefly directed to the degree of inflammability as compared with the volatile matter contained in the dust, and also to the liability to ignition by explosives in the absence of gas.

OBJECTIONS TO WATERING ROADWAYS.

The possibility of minimizing the coal-dust danger by watering the roadways has had to be at least temporarily disregarded in view of the prejudicial effect both on the health of the miners and on the economical working of the mines which that measure would unques-

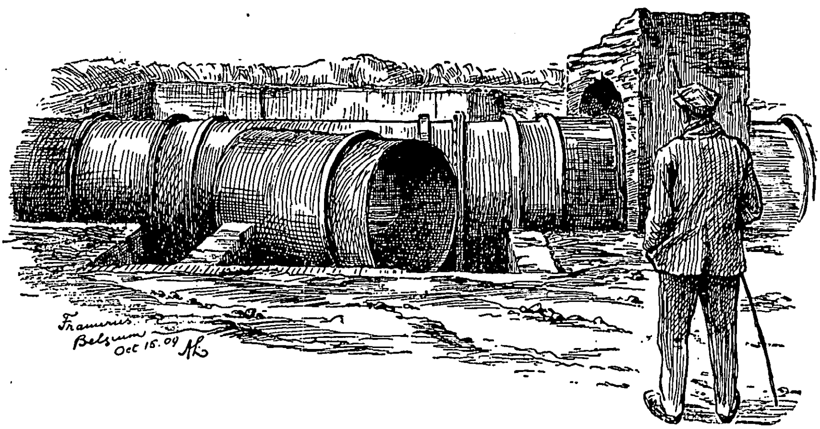


FIGURE 18.—Detachable section, Frameries gallery.

tionably entail. The Belgian mines are deep, depths of 800 meters being quite common, and many workings reach a depth of 1,000 and 1,100 meters. The temperature at that depth is about 45° C. (113° F.), and if charged with humidity in addition the atmosphere obviously would not be fit to work in. Besides, watering near the coal face, where it is considered to be most necessary in some cases, has been found to cause serious disturbances in the coal-bearing strata, and thus materially to raise the cost of production of coal, quite apart from the increased risk of fatal accidents from falls.[a]

"In the face of such grave objections," M. Watteyne explained, "we have not yet felt justified in recommending compulsory [universal] watering in Belgium."

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[a] Coal is extracted mainly by pick in the Belgian gassy collieries. Explosives (of permitted character) are used only in rock work. In brushing back in the passageways watering is generally done in the vicinity of the shot before firing it.—G. S. R.

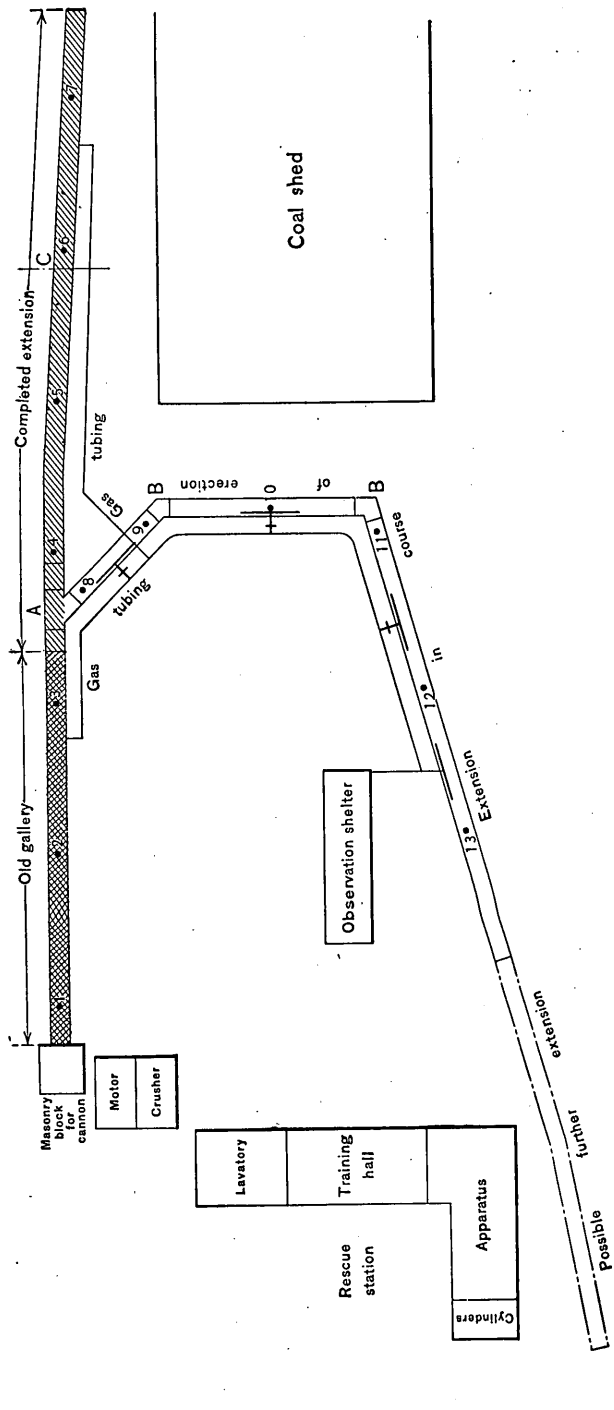


FIGURE 19.—Plan of Frameries gallery, showing proposed extension.

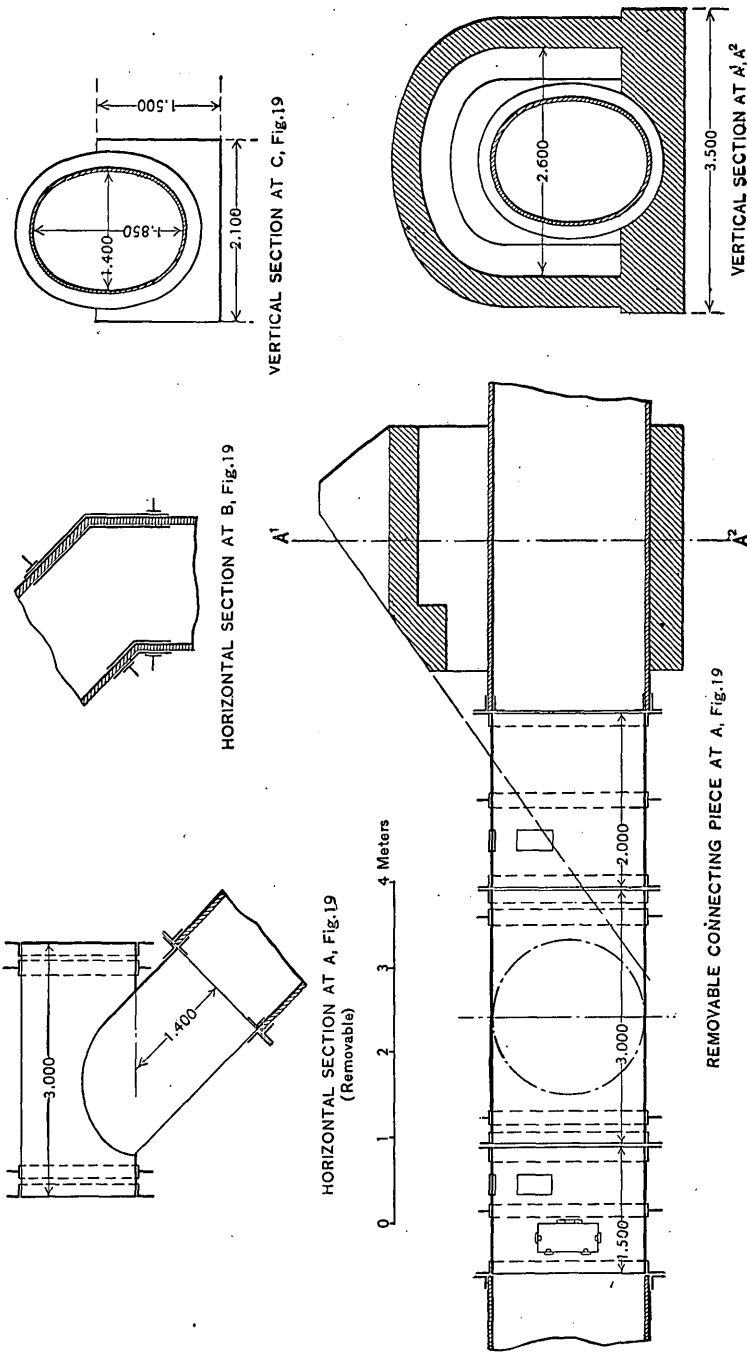


FIGURE 20.—Constructional details of extension to Frameries gallery.

TESTS OF EXPLOSIVES.

Pending future investigation of other means of preventing propagation of coal-dust explosions, due attention has at all events been given to means of preventing their initiation through explosives. A number of experiments have been conducted at Frameries with permitted explosives in order to test their relative safety in the presence of coal dust alone. These tests were carried out in the same way and under the same conditions as when testing in presence of fire damp, the temperature in the gallery being maintained as nearly as possible at 25° C.

The coal dust used for all tests was taken from one of the Agrappe mines, and contained 21 per cent of volatile matter. Some of the coal raised in Belgium contains as much as 35 per cent, but as the number of collieries where this coal is found is small, and the quantity of dust given off by the coal insignificant, the other quality of dust mentioned was chosen.

At first the practice was to bring the coal dust into a state of suspension, but ultimately this was found to be unnecessary, as the agitation caused by the shots proved sufficient.

The tests were made in the gallery at Frameries. The bore hole of the cannon was 55 millimeters, the charging density being kept within the limits of 0.4 and 0.6.

Freshly ground dust, passing through a No. 90 mesh (1,280 to the square centimeter), was used throughout, as it was found to be more inflammable than dust kept for fifteen or twenty days. The moisture, averaging from 0.5 to 2 per cent, was eliminated by drying the dust at a temperature of 30° C.

The gallery was charged with 150 grams of dust per linear meter. Higher dust charges did not materially affect the "charge-limite" of the explosives.

The test comprised ten shots for each explosive and these were fired on different days, so as to introduce different hygrometric conditions.

The result of this series of trials has led to a slight revision of the list of permitted explosives. Of 24 explosives tried, only seven proved less safe in coal dust alone than in gas; five of these belonged to the ammonium nitrate class, one to the chlorate class, and one to the carbonite class.

A revised list of permitted explosives now called "Explosifs S. G. P." (Sécurité-Grisou-Poussières), canceling all previous lists, is published in a ministerial circular dated October 18, 1909. The maximum charges are given for each explosive, both as to gas and as to coal dust; they vary from 300 to 900 grams. A minimum length of stemming is fixed at 20 centimeters. All cartridges must have the exact composition printed on their wrapper. Other precautionary measures in connection with shot firing remain in force.

Speaking of results generally, the "charge-limite" of permitted explosives fell in proportion to the increase of volatile matter contained in the coal dust. When inert dust was added the "charge-limite" rose.

EXTENSION OF GALLERY.

The gallery at Frameries has now been extended to a total length of 80 meters in one direction. The extension is connected with the old gallery by a section detachably bolted to both (fig. 18). When the full length of gallery is not required (for example, for testing explosives), the connecting piece, which rests on rails, is transversely run out of position. The annexed plans (figs. 19 and 20) show further proposed extension and details of construction.

INVESTIGATIONS IN PRUSSIA.

According to a recent announcement, the Coal Mining Corporation, of Westphalia, has decided to erect a trial gallery after the Liévin and Altofts type for the investigation of coal-dust explosions. The gallery will be built at Gneisenau, near Dortmund, where land has been bought for the purpose, and will be under the charge of Bergassessor Beyling, the present director of the Gelsenkirchen explosives testing station, which will also be removed to Gneisenau. The entire works will be completed in the spring of 1910. The Gneisenau coal-dust gallery will in all probability be of similar construction to that recently adopted at Liévin—an upcast section of armored concrete and a downcast gallery of 10-millimeter plate boilers, although for the latter portion some mining engineers are in favor of wood construction, which could be repaired more easily and at less cost. There will be two parallel lengths of gallery with crosscut connections at varying angles. A total length of 300 meters is mentioned.

Save such work as was feasible in the short Gelsenkirchen gallery (34 meters), more particularly in respect to the testing of explosives, no special study of coal-dust explosions has proved practicable at Mr. Beyling's station, but the matter will be taken in hand immediately when the new station is ready.

Preliminary tests with local coal dust have shown that while dust containing 24 per cent of volatile matter and passing No. 150 mesh was regularly ignited by 160 grams of gelatin dynamite, no ignition of the same dust took place when the gallery had been previously watered.

SPECIAL PREVENTIVE MEASURES.

BREAKING COAL BY DIRECT WATER PRESSURE.

One of the recommendations contained in the report of the royal coal-dust commission of 1894 was as follows:

> The substitution for explosive agents of similarly efficient methods of bringing down coal and stone which are quite free from the special dangers attending the use of those agents.

Attempts have frequently been made, both before and after, to give effect to this suggestion, but none of the methods proposed has so far proved successful. Certain experiments made many years ago at Saarbrucken at the suggestion of Herr Meissner, privy councilor of mines, at that time in charge of one of the state collieries in that district, may be cited as offering an interesting exception. This gentleman was, however, suddenly transferred to another sphere of activity, and the trials were discontinued. But recently the method has been again taken up in a Westphalian coal mine and put to practical tests with considerable success.

As the process comes under the head of "means for preventing coal-dust explosions," it may fittingly be described in this report. Indeed, as a preventive means, it may be said to start considerably ahead of all other remedies proposed, inasmuch as it is directed against the very source of coal dust, the solid coal itself. Briefly, it may be described as hydrostatic injection of the coal face (in German "Stosstränkung").

Into a bore hole, preferably bored at right angles to traceable divisions or slips in the coal, an iron water pipe is tightly wedged so as to prevent any back flow. Water is then turned on and allowed to permeate the coal face under a pressure of about 12 atmospheres. Unless the coal is absolutely impermeable the forced endosmotic action is so quick that in about fifteen to twenty minutes loud "working" of the seam is heard, followed shortly afterwards by a rush of water from some point offering the least resistance. The operation is then finished and the water is turned off.

As a rule the impregnated area is about twice or three times the cube of the depth of the bore hole, and where the coal is naturally interstitial in structure the whole of the affected area may be got by the pick.

In the Scharnhorst mine, near Dortmund, the writer saw the method practically employed in a seam of schistose coal 2½ meters thick and dipping at an angle of 80° from the horizontal. A bore hole was hand drilled in three divisions of different diameters, to provide the necessary "grip" for two conical wedges fixed on the water pipe. (See fig. 21.) The pipe was inserted into the bore hole and sledge-rammed home. The pipe was then connected by a hose to the water main of the pit (now easily accessible in all dusty pits in Germany) and the water was turned on.

After twelve minutes loud crackings were heard from several parts of the coal seam, and presently the water had found an outlet some 10 feet above the bore hole and came rushing down the coal face. It was stated that the one bore hole had loosened 36 half-ton cars of coal, all of which would be got by the pick and at about half the cost of blasting.

In reply to a question whether the method would prove practicable in less favorable conditions, it was stated that practically all seams, whether horizontal or perpendicular, were amenable to the treatment, but that not every coal could be got by pick with equal facility. But even if explosives had to be used afterwards, the effect of the injection was said to be such as to eliminate danger of using them, as far as coal dust was concerned. The coal was rendered just moist enough to prevent the formation of appreciable amounts of dust at

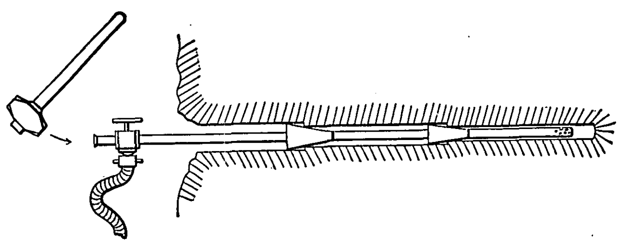


FIGURE 21.—Device for dislodging coal by injection of water.

the face, and all watering of the face could be dispensed with. The atmosphere in the workings never became dust-laden, hence there could be no clogging of lamp gauzes.

On returning toward the shaft the writer found the coal in passing cars clammy to the touch and haulage roads practically free from coal dust.

The double cone collars on the insertion pipe are said to be an improvement on Herr Meissner's method, and it is understood that patents have been applied for.

KRUSKOPF SPRAYING PROCESS.

Another method of staying accumulations of coal dust in mines was mentioned to me while in Westphalia, namely, the Kruskopf spraying process. The inventors, Messrs. H. and E. Kruskopf, of Dortmund, propose to wet the walls of underground roads with a certain chemical solution, or to suspend similarly soaked cloths from the roof of haulage and main roads, with a view to preventing deposits of dust and to stopping coal-dust explosions.

Although not without useful features, possibly in connection with protection zones, the invention has been presented in a form that is not likely to be adopted in practice, being too costly and of doubtful efficacy. The inventors refused to give particulars, owing to a pending application for American patent rights.

EXHAUST STEAM AS A PREVENTIVE OF DUST EXPLOSIONS.

By Frank Haas.

MOISTURE IN COAL DUST.

HOW MOISTURE PREVENTS EXPLOSION.

Exhaust steam is used to prevent coal-dust explosions on the theory that wet coal is more difficult to ignite than dry coal; also that a flame propagating through moist air suffers a greater temperature loss than one propagating through dry air.

To make coal dust absolutely and theoretically inert as a combustible—that is, to make a mixture of such composition that it would not ignite or consume from heat of its own generation—would require six or seven times its weight of water. This quantity of water is so large, causing, in fact, a condition practically equivalent to submergence, that its use is impossible. Fortunately the total quantity of heat which coal dust supplies is not the important factor in dust explosions, but rather the temperature of ignition. If the temperature is under control absolute safety may be attained. Before it is possible to ignite the combustible portion of coal dust or any other combustible containing water, physically or otherwise, such water must be evaporated.

RESISTANCE OF COAL DUST TO MIXTURE.

A very serious obstacle to complete success in preventing ignition, not only by introducing water by exhaust steam, but by any other method of application of water, is the property of coal to resist mixture with water, except to a very limited extent. It has been shown,[a] in experiments described by the writer, that extremely fine coal dust, after being submerged in water and thoroughly stirred with it, in a way that with almost any other material would result in a mixture, will rise to the surface so dry that a slight breath of air will throw it into a cloud, leaving the water almost clear.

[a] Haas, Frank, Is coal dust as such explosive? Mines and Minerals, December, 1908, pp. 227-229.

AMOUNT OF WATER ABSORBED BY COAL DUST.

Though the writers' experiments along this line have not been completed, it has been determined that coal dust does, to a certain extent, absorb moisture, which for gas coal (to be hereinafter considered) amounts to about 4 per cent.

In nominally dry atmosphere, the dust which was experimented with contained about 1.5 per cent of water. In the return air way of a mine in which the air was kept moist to the point of saturation, dust was collected from the side walls of the entry where it had lodged on the small projections of the solid coal. The moisture determinations obtained for this dust were extremely various, the minimum moisture being 4 per cent, the maximum 42 per cent, and the average 25 per cent. As the atmospheric conditions surrounding each particle were practically the same, the results should have been uniform if the content of water so determined were one of the physical properties of the dust. As they were not uniform, however, it was concluded that the minimum more nearly expressed the absorptive power of the coal and that any additional water was merely mechanically held in contact.

Now, 4 per cent is by far too little to be considered of much consequence, hence additional water uncombined with the coal is necessary for protection against ignition. From such of the writer's results as are available, however, it appears that the element of time enters into the question, and it is apparent that the longer dust is exposed (within a limited period) to water or saturated air the larger will be the quantity of water absorbed.

AMOUNT OF WATER REQUIRED IN MINE.

If the roof, floor, and sides of any entry are covered with a film of water of sufficient thickness, it will not only prevent the addition of fuel to an explosion, but will extinguish an explosion once started. This latter action, as it depends largely on contact, would not be instantaneous, but would be effective in a comparatively short distance if the wet conditions were maintained. To demonstrate this, let us assume that in an entry 10 feet wide and 6 feet high there is a film of water 0.025 inch thick on floor, roof, and sides. In one linear foot of such entry there would be 32 square feet covered by this film, making in all about 115 cubic inches, or 4.25 pounds of water. Let us suppose an explosive flame passes through this entry, say, at a temperature of 4,000° F. and at a pressure of 3 atmospheres. If the specific heat of the gases be taken at 0.3, the weight of a cubic foot of the gases at normal pressure and temperature would be approximately 0.1 pound. At normal pressure and a temperature of 4,000° F. (absolute) the water vapor would weigh roughly $\frac{0.1 \times 460}{4,000}$ or 0.011 pound per cubic foot. At 3 atmospheres pressure the weight would be 0.033 pound per cubic foot. The heat units in 1 linear foot of entry 10 by 6 feet would be 2,376 B. t. u., since the temperature (4,000) times the weight (0.033×60) times the specific heat (0.3) equals 2,376.

It requires 756 B. t. u. to evaporate 1 pound of water, hence 2,376 B. t. u. would evaporate about 3 pounds of water. If, then, a film of water 0.025 inch thick is maintained, which is equivalent to 4.25 pounds of water per linear foot, to vaporize this water would absorb all the heat of the explosion and drop the temperature well below the ignition point of the coal dust.

It may be noted at this point that the smaller the area of the entry the less is the thickness of the film of water necessary. Hence open spaces in a mine should be avoided as much as possible. Mines that have idle rooms or unpillared sections under ventilation introduce an unnecessary element of danger in spite of the fact that the force of an explosion may be dissipated in a large opening.

DISTRIBUTION OF MOISTURE.

It is difficult or impossible to maintain or even establish a uniform film of water over the surface of the coal. Coal dust and solid coal so resist the contact of water that it can not be applied to them in better form than as "drippers" on roof and side walls. It is possible to provide in this form an amount of water equivalent to the film, but its effectiveness is not so complete. To establish such a condition in a mine is merely a matter of mechanical labor, but to maintain it requires vigilance with constant labor, or else an atmosphere either neutral or supersaturated with moisture.

EXHAUST STEAM IN OPERATION.

VALUE FOUND BY ACCIDENT.

In connection with the following account of experiments and observations the reader should have in mind the nature of relative humidity and the general relations of air and water vapor.

The introduction of steam into the air current in the Fairmont region began about three years ago. At that time the danger from coal dust was not so seriously considered, and the steam was not introduced for the purpose of moistening the coal dust. It was rather for convenience to get rid of the exhaust steam from a pump and hoist engine rather than carry it up a shaft. The effect of the steam in keeping the entry moist was observed, and when the question of watering the mine was more seriously considered a year or so later it was decided to continue to utilize the means that had been accidentally discovered.

RECORDING INSTRUMENT.

As no records of temperature and humidity of the atmosphere of the vicinity were available, it was necessary to produce such records extending over all the seasons of the year. Individual observations taken periodically were obviously insufficient, considering the large fluctuation in comparatively short times. For a recording instrument a hygrothermograph, manufactured in Baltimore, Md., was used. This instrument records both temperature and humidity for weekly periods. No difficulty was anticipated with regard to the temperature, but the calibration of the instrument for humidity was attempted with considerable misgivings, as the actuating part is a hair that expands or contracts in direct proportion to the relative humidity of the atmosphere. However, the instrument was set up in a covered box and checked with a standard psychrometer for temperature and humidity at least twice a day for several weeks. It was considered sufficient to test the instrument at the maximum and minimum points of both temperature and humidity, which occurred usually at 8 a. m. and 4 p. m. After adjustment and thorough calibration this instrument and two others that were bought later gave very satisfactory results. While far from perfect, it is nevertheless the best known to the writer for continuous record and gives results well within the limit of error of other observations necessary for the investigation.

RECORDS OF OUTSIDE TEMPERATURE AND HUMIDITY.

In figure 22 is presented, together with the results of the weekly records from the instrument, the daily range with maximum and minimum of temperature and humidity of the outside air at Fairmont, W. Va., from June 1, 1908, to June 1, 1909. In this chart the water vapor has been calculated and recorded in gallons per 100,000 cubic feet. This is simply a convenient figure for comparison, as 100,000 cubic feet is ordinarily a practical unit for mine ventilation and is one that makes the quantities of water whole numbers rather than fractions. The chart shows at a glance the difference between the quantity of water vapor held by the atmosphere in winter and in summer.

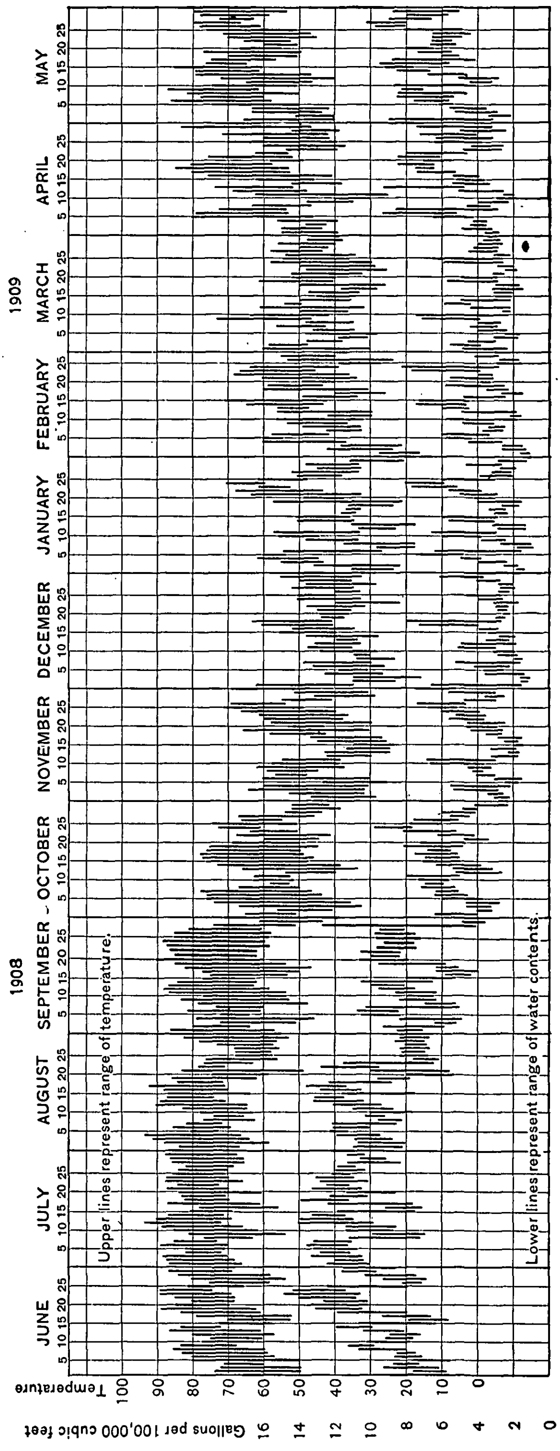


FIGURE 22.—Atmospheric temperature and water-vapor chart.

MOISTURE CONTENT OF RETURN AIR.

Concurrent with those of outside temperature and humidity, observations of the temperature and humidity of the return air of certain large mines of the Fairmont Coal Company were taken. These observations were free from daily fluctuations—in fact were so regular and uniform that monthly averages, as shown in figure 23, give the information in sufficient detail. In this chart, it will be noted, are the daily averages, also calculated in gallons per 100,000 cubic feet, of the vapor content of the outside atmosphere and of the air in the return air way.

DEFICIENCY OF WATER TO BE SUPPLIED.

Such a chart shows at once the excess and deficiency of water in a mine air current at different periods of the year. It indicates that an ordinary mine ventilated with 150,000 cubic feet of air per minute will show an accumulated deficit of water amounting to 2,000,000 gallons per year. Two months during the year the quantity of water taken into the mine by the air is in excess of that taken out. This period is approximately from the middle of June to the middle of August. Hence it appears that artificial means of watering are necessary during the greater part of the year—from August 15 to June 15. During that time at least 2,000,000 gallons of water must be supplied. This figure, of course, is based only on one year's observations, and may be greater or less from year to year, yet the indications are that the observations in the second year will practically coincide with those of the first year.

In supplying the deficiency of water, the aim should be to cover the maximum deficiency for any period rather than the minimum at any one time. During the year from June

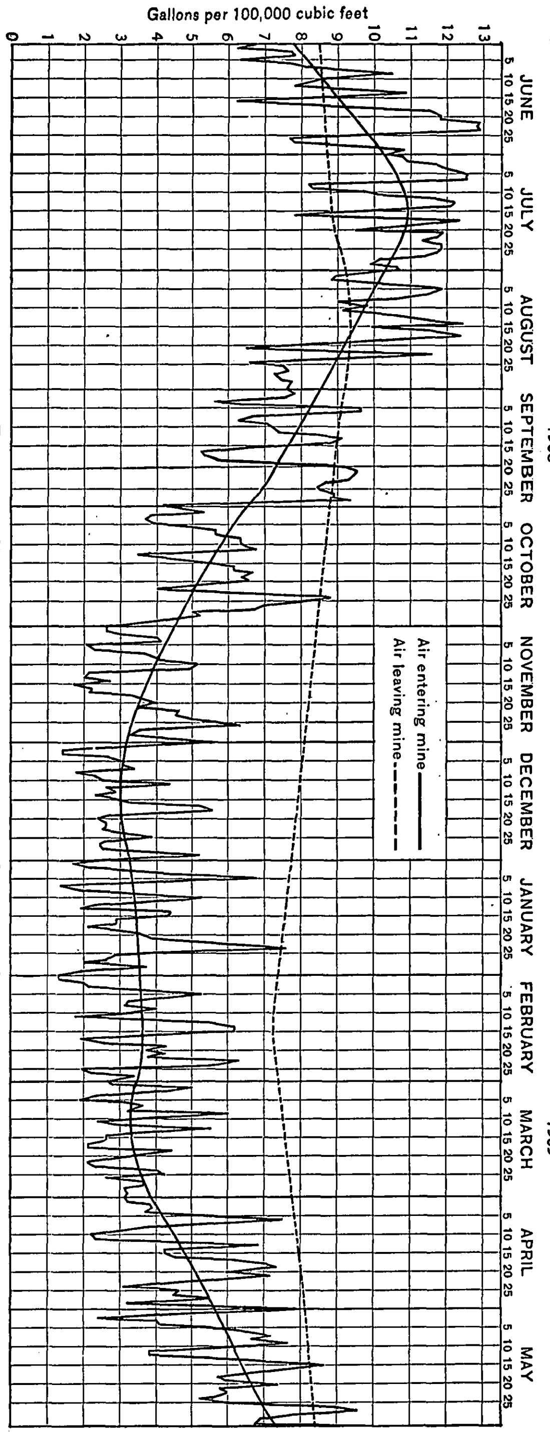


FIGURE 23.—Chart of water content of outside air and return air of mine.

1, 1908, to June 1, 1909, the minimum average temperature for one day was 21° and the minimum average content of water vapor per 100,000 cubic feet of air was equivalent to 1.3 gallons of water. The lowest weekly average temperature was 34° with a concurrent average humidity of 3 gallons, and the lowest monthly average temperature was 39° with 3 gallons of water. As the deficiency and excess of water in a mine are more or less cumulative, it would be safe to take the weekly average as a basis for calculating the quantity of heat and moisture to be supplied by artificial means.

According to the records, the temperature of the return air current during the coldest weather of the year was 55°, and it carried 7.2 gallons of water per 100,000 cubic feet. If, then, sufficient heat were constantly supplied to raise the intake temperature from 34° to 55°, and sufficient water to raise the quantity from 3 to 7.2 gallons per 100,000 cubic feet (the rate per minute), the conditions would be such as to provide an excess of water in the mine and keep the mine air saturated. Holding to a unit of 100,000 cubic feet per minute, we find that it will require 39,900 B. t. u. per minute and 4.2 gallons of water.

AMOUNT OF HEAT AVAILABLE.

Monongah No. 8 mine fan during these observations was making about 135,000 cubic feet per minute with 1½-inch water gage. By the common formula this required about 30 horsepower; by indicating the engine, however, it was found that 55 horsepower was actually supplied. This difference is due to the great loss in efficiency in running a large engine below capacity. If 55 horsepower is supplied, with a steam pressure of 100 pounds, and consumes 35 pounds of water per minute per horsepower, about 1,500 B. t. u. is used by the engine per minute for power and about 31,000 B. t. u. is available for heating the air if the exhaust steam is turned into the mine. This amount of heat would be sufficient to increase the temperature 12°, or from 34° to 46°. It would also furnish 3.85 gallons of water per minute and would raise the water content of the air 2.8 gallons, or from 3 to 5.8 gallons per 100,000 cubic feet of air.

EFFECT OF STEAM ON MINE AIR.

These figures are more or less theoretical, and though both the heat and the water of the exhaust steam enter the mine it does not necessarily follow that all of both are available for the saturation of the mine air.

OBSERVATIONS OF MINE AIR WITHOUT EFFECT OF STEAM.

It was anticipated that the full effect, as calculated above, would not be obtained, and in order to test the efficiency of the exhaust steam two recording instruments were placed in the mine, one in front of the blowing fan and the other about 400 feet beyond the fan. A week's record was produced during the cold season under normal conditions; that is, without the use of the exhaust steam. The two records are reproduced in figure 24, which shows two temperature curves and two representing humidity, the latter being expressed in percentages (relative humidity) instead of gallons of water, as in the previous charts.

Exhaust steam had been in use the previous week and was turned off six hours after the records began, which accounts for the 100 per cent humidity for the first six hours. The distinctive feature shown by this chart is the equalizing effect of 400 feet of entry on both the temperature and humidity. The average temperature 400 feet inside the mine is but slightly higher than that at the fan, but it does not show the sudden fluctuations of the latter. The humidity inside of the mine was naturally affected by the previous wet conditions, but the effect had more or less disappeared later in the week. Like the

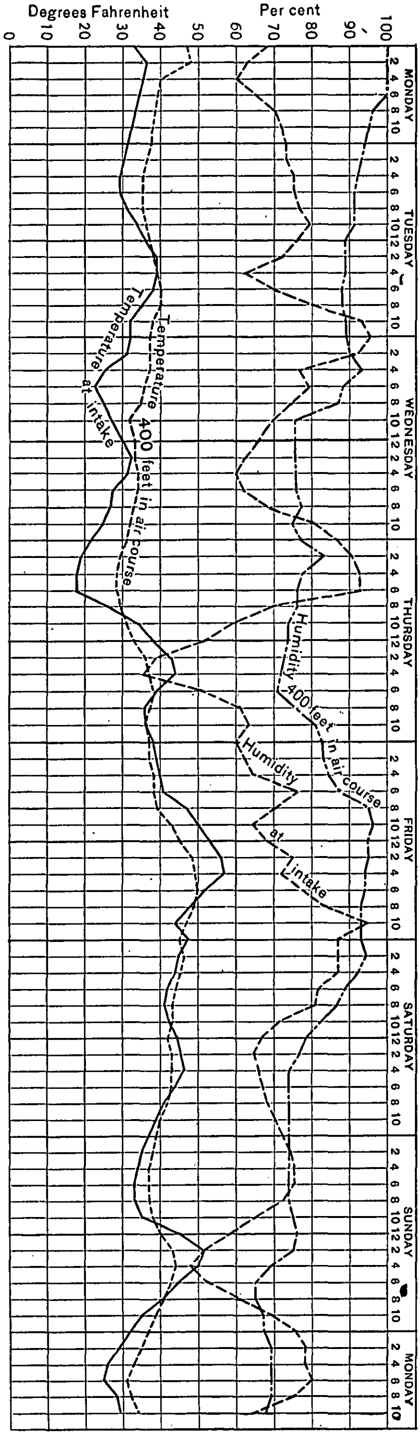


FIGURE 24.—Chart of temperature and relative humidity of intake air with exhaust steam off and heater off.

temperature, the humidity within the mine showed a tendency to equalize itself and produced a more nearly straight line. The fact that it ran higher than the humidity at the fan is due entirely to the previous wet condition.

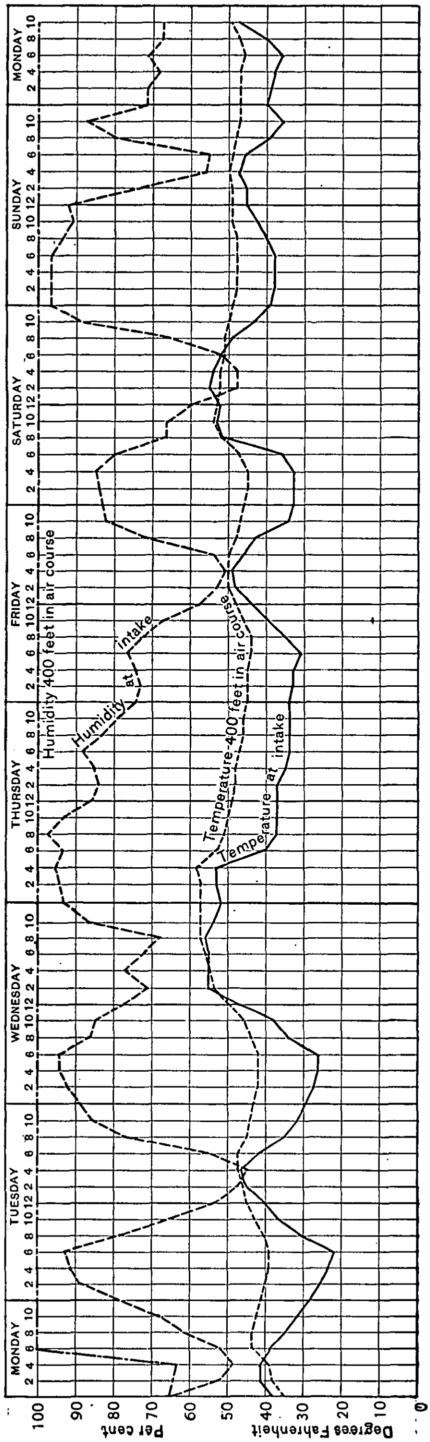


FIGURE 25.—Chart of temperature and relative humidity of mine air with exhaust steam on and heater off.

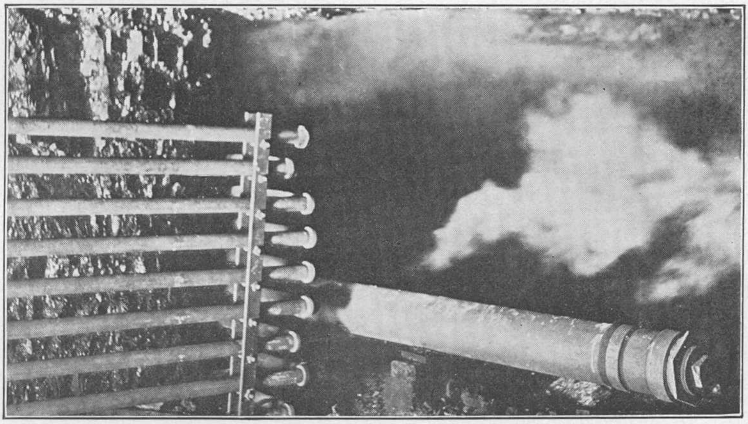
OBSERVATIONS OF EFFECT OF STEAM.

A record (fig. 25) was also taken with the instruments in the same position and with the exhaust steam going into the mine. The fan instrument was to show the atmospheric humidity, while the instrument 400 feet inside the mine showed the full effect of the steam. The exhaust steam was not turned into the mine until six hours after the instruments started recording.

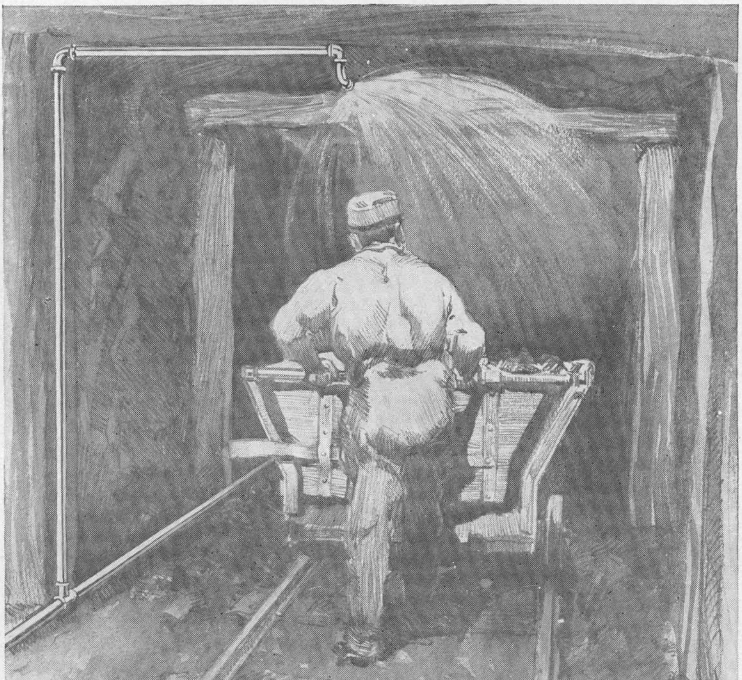
The moisture made itself apparent immediately by saturating the air and holding the humidity at 100 per cent, irrespective of the outside condition. The temperature showed an average increase of only 8°.

EFFECT OF HEATING MINE AIR.

It is to be noted, however, that the increase in temperature was greatest when the outside temperature was lowest. The amount of heat supplied being uniform, a constant increase in temperature should be expected if there were no disturbing elements present.



A. RADIATOR AND STEAM PIPE IN USE, MONONGAH NO. 8 MINE.



B. A SPRAY IN AN ENTRY.

These curves, showing plainly that disturbing elements of considerable magnitude did exist, led to a separate study, which resulted in important conclusions, to be noted later in this paper. The principal fact brought out was that there was not sufficient heat supplied to establish a normal temperature of 55° during this season of the year. To supply this deficiency of temperature it was then decided to put in an air preheater. This was done by placing 1,200 feet of 2-inch pipe in nine coils around a coal pillar, which happened to be conveniently situated behind the fan, and between the fan and the point where the exhaust steam was allowed to escape into the air (fig. 26). In Plate XIV, *A*, is reproduced a photograph showing one corner of this radiator and the exhaust-steam pipe in operation.

An endeavor was made to measure the heat supplied by this radiator in order to get a practical figure for the size or length of pipe required to heat a unit volume of air. This was found very difficult

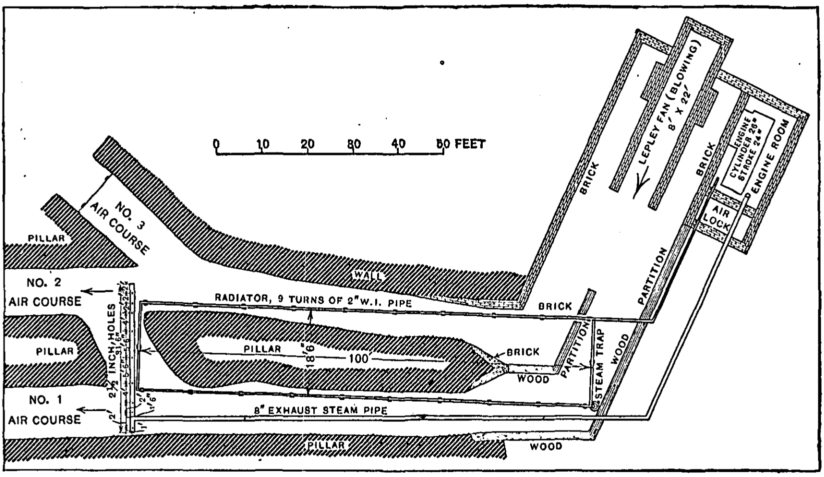


FIGURE 26.—Plan of intake at Monongah No. 8 mine, showing arrangement of live-steam heater and exhaust-steam pipe.

to accomplish, and while several methods were tried they were not pursued far enough for satisfactory results.

Figure 27 shows the difference in temperature and vapor contents between the outside air and the air 400 feet from the fan, when both the exhaust steam and the heater were used. The air shows complete saturation, while the temperature was raised on an average 19° F. A disturbing element was noted in this experiment, as in that in which only the exhaust steam was used. There was evidently another source of heat present which affected the results more than either the exhaust steam or the heater. It was noticed that the difference in temperature was less when the instruments were moved nearer the intake and greater when they were moved farther away. The item of radiation of heat from the side walls of the entry, which at first was considered inappreciable, developed into the most prominent factor.

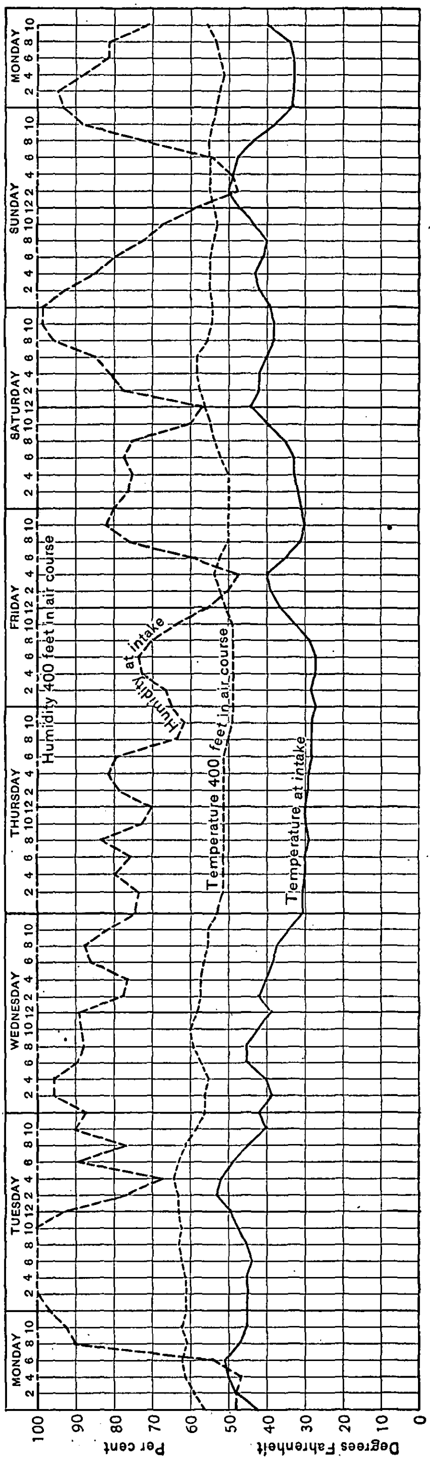


FIGURE 27.—Chart of temperature and relative humidity with exhaust steam on and heater on.

HEAT RADIATED FROM SURFACE OF ENTRIES.

To investigate the effect of radiation on the temperature of intake air, we selected a mine (Monongah No. 6) which had two parallel intake headings without a split for over 2,000 feet. Along one of these entries at intervals of 200 feet thermometers were hung, and during a night when outside temperature conditions were favorable observations of time and temperature were frequently taken at each of these thermometers. The average velocity was determined by vaporizing carbon bisulphide at a certain time at the intake, and having another observer record the time the scent reached the end of the heading. The area of exposed surface and the volume of each 200-foot section of the double entry were calculated. Figure 28 shows graphically four sets of the observations. The radiation from the side walls is greatest where the difference in temperature is most. The rate of increase of temperature is dependent on so many quantities and conditions that it could hardly be attempted to throw them all into one equation. The area exposed, the velocity and the volume of air, and the original temperature are the principal factors. The temperature of the side walls is not uniform, however, and is considerably, though temporarily, affected by changes in atmospheric temperature. The unknown factor makes the application of an equation impossible.

The fact demonstrated by these observations is that radiation from the side walls has considerable effect in raising the temperature of the air. In this particular test in 4,000 feet of mine entry over 30,000 British thermal units had been radiated per minute, which would be equivalent to heat derived from burning over a ton of coal per day. It was the utilization of this radiated heat that led to the abandonment of the preheater. This can be done in every mine where the air travels over 3,000 feet at a velocity not to exceed 500 feet per minute before it reaches the men to be served with ventilation. For example, in the mine in which the observations were made, if suffi-

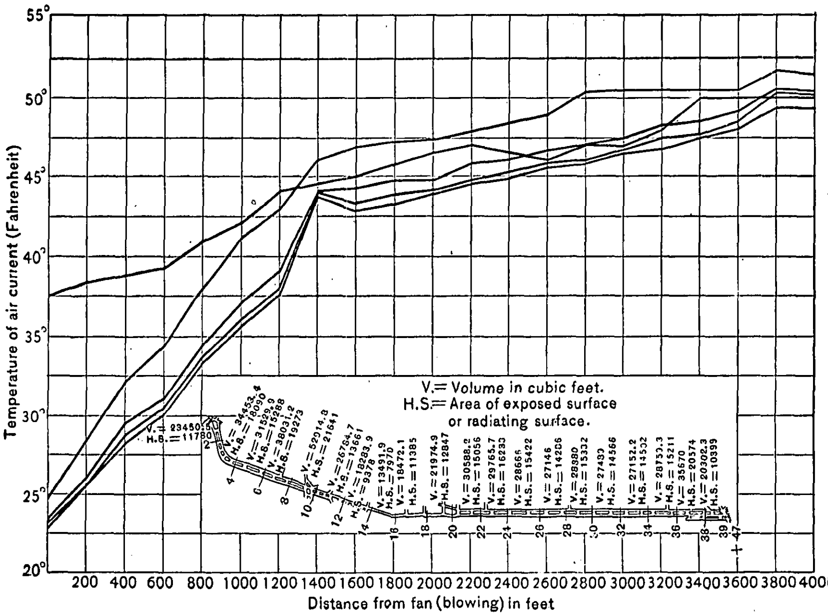


FIGURE 28.—Progressive change of temperature of air current due to radiation. Average velocity, 453 feet per minute; volume of air, 66,432 cubic feet per minute.

cient exhaust steam were introduced at the end of the 4,000 feet the additional heat would raise the temperature to or above the normal mine temperature, even with an outside temperature of 25°. The conditions for complete saturation would be continuously in force, and the result would be a wet mine, not only theoretically wet, but looking and feeling wet enough to satisfy the practical man. There is, however, serious objection to carrying an exhaust-steam line 3,000 or 4,000 feet into a mine, on account of the back pressure on the engine and the probability of adverse grades; in fact, the practical difficulties in the way are sufficient to condemn the method. It is possible, however, to avoid this objection by a sacrifice of part of the moisture.

MOISTURE CARRIED AS FOG.

The capacity of air to carry water vapor is limited by its temperature, but the quantity of water that can be carried mechanically in the form of a fog is limited only by the velocity of the air current.

The relative proportions of water that can be carried in the form of vapor and as fog have not been determined. The proportions can very readily be determined, however, and observations were to be carried out on this point during the winter of 1909–10. The first effect of exhaust steam on air would be the saturation of the air with water vapor, the remainder of the steam being deposited as water or carried in the form of a fog. This fog near the inlet of the exhaust steam is in the form of a dense white cloud, so thick as to hide the light of a mine lamp only a few feet away. In traveling with the air from the exhaust-steam intake the cloud gradually becomes thinner; farther in the air is clear near the side walls and the roof, the fog traveling in the center of the entry in the form of a cylinder with a revolving forward motion. The cylinder or cone form gradually grows less in diameter, ending in an indefinite point. This approximate point has been designated the fog line. It is remarkable how promptly the position of this fog line responds to a rise or fall of outside temperature by shifting backward or forward.

For practical purposes and comfort to miners it is advisable to keep this fog line from advancing to the working face. This can be done in several ways—first, by reducing the volume and thereby the velocity of the air current; second, by increasing the number or area of air ways; third, by so changing the air courses that the distance to the working face is increased. Conditions in a developed mine where a blowing fan is used would be very unusual if no one nor any combination of methods could be utilized to bring the fog line within the limits of practical application.

QUANTITY OF STEAM NEEDED FOR SATURATING MINE AIR.

In the observations made and the results obtained so far the necessary quantity of exhaust steam for a unit quantity of air has not been definitely determined. An approximately correct figure was assumed to be three-quarters of a horsepower of exhaust steam (from a simple reciprocating engine) for each 1,000 cubic feet of air supplied. The size of the mine does not enter into the assumption. In mines of small development the ratio of fan horsepower used to quantity of air supplied is less than that noted above as necessary for saturation. In mines older and of larger developed area, the ratio may be greater than necessary. In Monongah No. 8 mine, in which most of the experiments have been conducted, the ratio is about 0.4 or only 53 per cent of what is necessary. In order to make up this deficiency it is intended to put a brattice immediately behind the fan, with sliding doors, so that the area can be contracted to a point where the engine will indicate 100 horsepower while still delivering the same quantity of air.

It has been suggested that for the additional steam live steam be used, thus saving the extra work of the engine or replacement by a large engine. The effect would be the same, but its regulation would not be under control, and, furthermore, there would be nothing to indicate whether the live steam was actually in continuous operation. Every fan is or should be equipped with a recording water-gage chart, and if the steam goes through the engine this water-gage chart will indicate both the quantity of air supplied and the amount of exhaust steam used, with sufficient accuracy for practical purposes. It would be much too easy for a sleepy or lazy fireman to shut off the live-steam pipe with no one the wiser for it, and this is sufficient reason for putting the steam through the engine. It is true that steam meters could be used, but these would show only the total quantity supplied, and unless a recording instrument could be added they would fail in their purpose. Furthermore, additional horsepower is required only in exceptional cases, and in them only temporarily.

To apply the method of watering mines with exhaust steam, outlined in the preceding pages, a blowing fan is necessary. The method can not be applied with an exhaust fan because of the dense fog which necessarily occurs at the intake and for some distance in from the mouth of the mine. In most mines it is possible to change from exhaust to blowing ventilation, and if other conditions do not prevent it would pay to do so. There are strong arguments in favor of exhaust fans in some mines, particularly mines that were originally planned for such ventilation and worked by methods adapted to it. In such mines an air preheater must be used. While experiments along this line indicate that preheating can be successfully done, it will require constant attention for its control, besides the expense of erecting and maintaining the air heater.

USE OF STEAM AND WATER SPRAYS IN OKLAHOMA MINES.

By Carl Scholz.

PURPOSE OF INQUIRY.

The writer's investigations in the Oklahoma field were begun because of the comparatively large number of mine fires and mine explosions in that district; also because of the trouble from falls of roofs, which add constantly to the dangers and cost of mining operations.

A tabulation of the accidents in mines of the Rock Island Coal Mining Company resulting from explosions, mine fires, windy shots, and roof falls drew attention to the fact that the accidents and expense from roof falls diminished with the arrival of cold weather, but that the number of accidents from the other causes mentioned increased. The writer was prompted to continue his inquiry in this direction with a view to determining means of preventing, if possible, the disintegration of roofs in summer and the explosions and mine fires in winter.

MOISTURE AND MINE AIR.

The roof falls were ascribed to the deposits of moisture or "sweat" on the roof and ribs, at first near the intake, then slowly extending farther into the mine. With the return of cold weather the moisture gradually disappeared, the rate of appearance and disappearance varying with the local climatic conditions.

A series of observations made with thermometer and hygrometer, both inside and outside the mines, showed that during the summer, when the temperature outside averaged 85° F. for twenty-four hours, with a maximum of 95° or 100°, the mine temperatures fluctuated between 70° and 78°; and that during the winter, with a temperature of 40° to 50° outside, the mine temperatures ranged from 60° to 67°, the exact temperature necessarily depending somewhat on the extent of the mine. In a new and less extensive mine the fluctuations follow more closely the outside temperature; in an older mine, with more extensive workings, the return air does not show many degrees difference between summer and winter.

At about the time that some experiments were being conducted in one of the mines of the Rock Island Coal Mining Company, water overflowed from one of the adjoining mines and flowed down a slope 2,000 feet to the shaft of the mine under investigation. This slope was the intake air way of the mine. Apparently the contact of the air with the water tended to reduce in this mine the number of local dust explosions and gas ignitions from black-powder shots, without increasing the number of roof falls. The absence of effect on the roof was attributed to the uniformity of the humid condition of the mine air, in contrast to the former extreme changes from winter to summer, or during shorter intervals.

This observation led to an investigation of the relation of the humidity of mine air to dust explosions. Cold air entering a mine has a low capacity for absorbing water. As it is warmed by contact with the warmer mine walls its capacity for moisture increases rapidly, so that it draws the moisture from the mine and leaves the dust and timbers and faces of the coal dry. Hence in winter water is carried from the mine by the air current, and in summer moisture is deposited on the roof and walls of the mine, or the mine "sweats."

APPLICATION OF STEAM AND WATER SPRAYS.

The writer had a steam coil installed near the top of an intake shaft for use in cold weather, consisting of several hundred feet of pipe through which exhaust steam was passed. The moisture condensed from the steam was carried in with the downcast air current, heating the air to some extent and adding to its humidity. However, the amount of steam that could be exhausted into the hoisting shaft was limited by the necessity of having the atmosphere at the bottom clear of fog. This was found not to be sufficient. The mine continued dry within 1,000 feet of the intake. Water sprays were tried with good results, and then installed more extensively. As the main intake slopes were naturally more or less wet, the working faces farthest down the slope, but first on the air currents, were not troubled with drying out as were those farther along the air current. Hence it was necessary to place sprays at intervals for remoistening or humidifying the air, the places being determined by the hygrometer or wet and dry bulb thermometers. In general it was found that a relative humidity of over 85 or 90 per cent gave the working places a satisfactory degree of dampness. Such increased humidity lessens the chances of a dust explosion, both because it dampens the dust and because in the presence of a blown-out shot a higher temperature would be required for ignition of both gas and dust by reason of the higher percentage of water vapor in the atmosphere.

The spray heads found to be best were those of a type that will make as fine a spray as possible for more ready absorption by the air currents. They should be of such design that they will not clog easily. Clogging is one of the chief troubles in the use of these sprays, and close attention must be paid by the foremen to see that they are running freely. This takes only a moment's attention. A spray head in a heading is shown in Plate XIV, *B*.

On a main intake and haulage slope a different type of spray has been tried—a short vertical pipe with a groove cut in it and holes perforated at intervals in the thin metal left at the back of the groove. These holes are easily cleaned by running a point down the groove. This spray pipe is placed at one side of the road and throws the spray against the air current.

The arrangement of sprays in the mine where the principal experiments were conducted is shown in figure 29.

An example of some of the results obtained is shown in the table below. The readings were taken by the ordinary dry and wet bulb thermometer, the air volume was determined with an anemometer, and the barometric fluctuations were noted at the surface, at the head of the most important splits, and at the foot of the upcast.

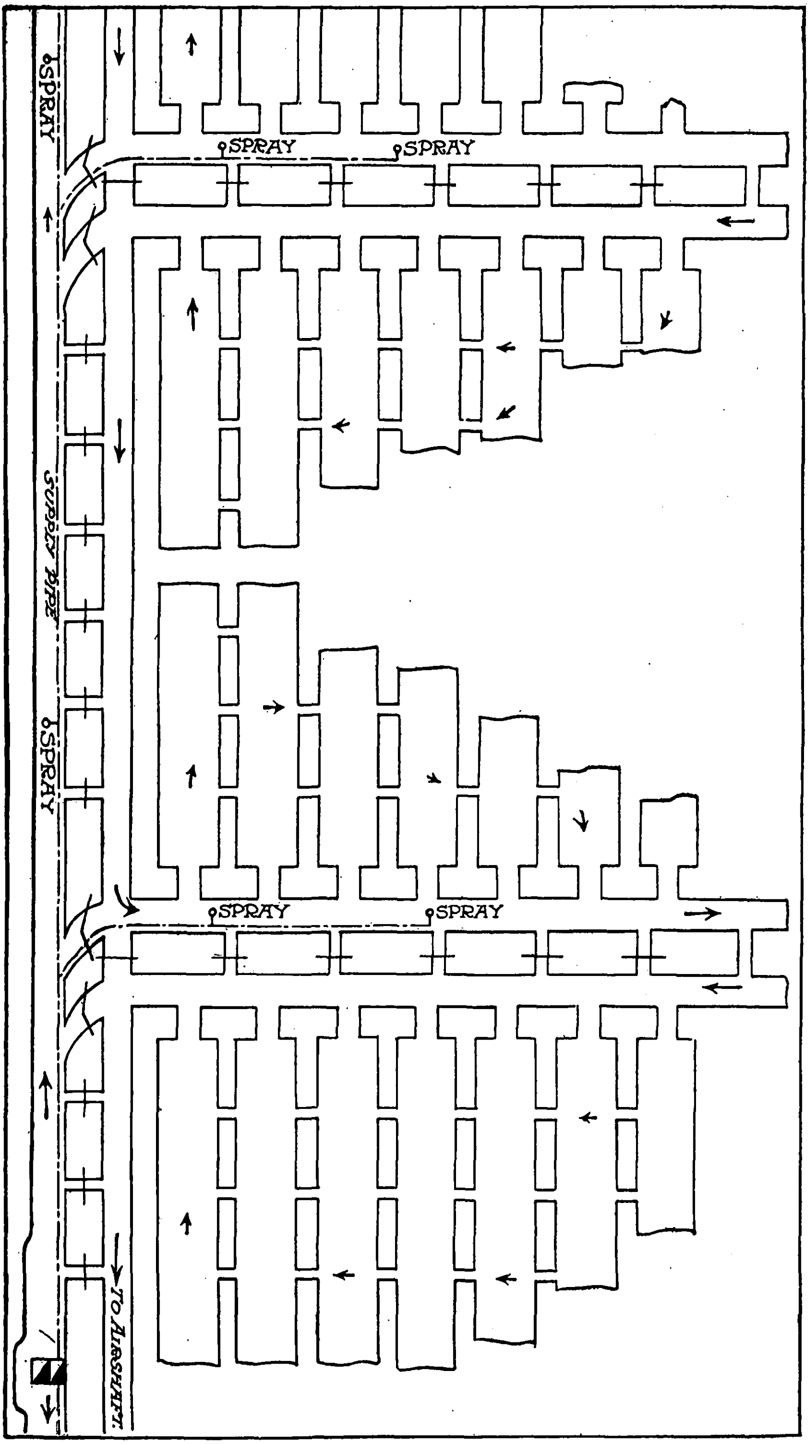


FIGURE 29.—Location of sprays in entries, No. 8 mine, Hartshorne, Okla.

Observations on air in mine of Rock Island Coal Mining Company in Oklahoma.

Date.	Location.	Time.	Temperature.	Relative humidity.	Volume of air per minute.	Quantity of water per minute.	Total water contents, 24 hours. Downcast.	Total water contents, 24 hours. Upcast.
			°F.	Per cent.	Cubic feet.	Gallons.	Gallons.	Gallons.
Jan. 4, 1908	Surface	8.50 a. m.	48	90	1,000	0.0576	4,976	9,180
	Slope 26 [a]	9.20 a. m.	65	84	25,000	2.465		
	Air shaft [a]	10.00 a. m.	67	85	60,000	6.375		
Feb. 25, 1909	Surface	4.17 p. m.	58	34	1,000	.03148	2,629	9,663
	Slope 26 [a]	4.30 p. m.	55	64	26,000	1.3977		
	Air shaft [a]	4.45 p. m.	68	89	58,000	6.7106		
Sept. 14, 1909	Surface [b]	11.40 a. m.	82	36	1,000	.07164	6,498	13,275
	Slope 26 [c]	12.20 p. m.	74	95	24,000	3.5124		
	Air shaft	12.50 p. m.	74	95	63,000	9.219		

[a] Sprays in operation; roads well sprinkled. [b] Weather very dry. [c] "Sweat" disappearing rapidly.

It may be observed from the above tabulation that the method of exhaust ventilation was employed in this mine, the hoisting shaft being the intake. It is the writer's opinion that gassy or dusty mines are preferably ventilated with an exhausting fan. By this method the haulage roads have fresh air, and the following marked advantages result: (*a*) Electricity and lights are kept out of the return-air current, which is important if the mine makes gas; (*b*) the intake is under inspection, so that falls will be taken care of promptly; (*c*) in case of mine fires or explosions fresh air comes into the main entrance, where there are usually the best facilities for quick escape.

COST OF WATER SPRAYS.

Objection has been made to the spraying system on account of cost of installation. While no general estimate of the necessary outlay can be made, as each mine has its own peculiar conditions, an average of 5,000 feet of 1½-inch pipe, with 6 to 10 spray heads, should be sufficient to saturate the air current in a mine producing 500 to 800 tons per day. The cost of operation is slight. The labor charge is limited to that required for the examination of the spray heads to see that they are not clogged. This may be made one of the duties of the mine foremen.

The chief cost is in the extension of pipe lines and sprays and in supplying water. If the mine makes water that is not too acid to use, the cost of supplying water is insignificant.

A test will readily convince a mine management of the improvement in the atmosphere of a mine in which sprays have been introduced. It is purified and free from dust, and by dampening the coal dust one of the great sources of danger of an explosion is minimized.

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