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EXPLOSION TESTS OF PITTSBURGH COAL DUST IN THE EXPERIMENTAL MINE 1925 TO 1932, INCLUSIVE

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INTRODUCTION AND SUMMARY

Details of explosion tests in the Experimental mine before 1925 were given in Bulletins 56,[5] 167,[6] and 268,[7] which covered consecutive periods of time. The nature of the work during the present period and the exigencies of publication have made it desirable to issue three bulletins dealing with subdivisions of the general problem of the explosibility of coal dust and the prevention of explosions in coal mines. The first of these was Bulletin 353,[8] dealing with tests of rock-dust barriers; the second is the present paper, which reports tests made to determine the effect on the explosibility of Pittsburgh coal dust of altering conditions under which the tests were made; the third, dealing with tests of dust prepared from approximately 20 coals taken from beds in mines in different parts of the United States, will follow after the completion of testing in progress at the time of writing.

Technical Papers 386 [9] and 464 [10] were issued during the present period. The former dealt with tests of dusts prepared from coals received from Utah, and the latter gave a summary of results to 1929. The results of other investigations of urgent nature whose conduct interrupted the progress of explosion tests from time to time were also published. The more important of these were an

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[4] Coal-mine superintendent, U.S. Bureau of Mines.

[5] Rice, George S., Jones, L. M., Clement, J. K., and Egy, W. L., First Series of Coal-Dust Explosion Tests in the Experimental Mine: Bull. 56, Bureau of Mines, 1913, 115 pp. Describes the construction and equipment of the mine and gives results of the first 15 tests.

[6] Rice, George S., Jones, L. M., Egy, W. L., and Greenwald, H. P., Coal-Dust Explosion Tests in Experimental Mine, 1913 to 1918, Inclusive: Bull. 167, Bureau of Mines, 1922, 639 pp. Describes developments during the period and gives results of approximately 500 tests. These tests dealt with explosions of pure coal dust, effectiveness of different incombustible dusts in preventing propagation of explosions, explosibility of dusts prepared from coals taken from different beds, origin of explosions at different points in the mine, and effectiveness of rock-dust barriers. Various methods of preventing or checking the spread of explosions are discussed.

[7] Rice, George S., Paul, J. W., and Greenwald, H. P., Coal-Dust Explosion Tests in the Experimental Mine, 1919 to 1924, Inclusive: Bull. 268, Bureau of Mines, 1927, 176 pp. Gives an account of changes at the Experimental mine during this period and the results of approximately 225 explosion tests, most of which were of coals obtained from different beds throughout the United States.

[8] Rice, George S., Greenwald, H. P., and Howarth, H. C., Tests of Rock-Dust Barriers in the Experimental Mine: Bull. 353, Bureau of Mines, 1932, 81 pp. Gives results of approximately 350 tests of rock-dust barriers of different types and classes made to determine their proper design and effectiveness when used in connection with rock dusting.

[9] Greenwald, H. P., Explosibility of Coal Dust from Four Mines in Utah: Tech. Paper 386, Bureau of Mines, 1927, 20 pp. Gives results of tests of dusts prepared from coal obtained from four mines in the Book Cliffs field.

[10] Rice, George S., and Greenwald, H. P., Coal-Dust Explosibility Factors Indicated by Experimental Mine Investigations, 1911 to 1929: Tech. Paper 464, Bureau of Mines, 1929, 45 pp. Summarizes information obtained on seven factors influencing the explosibility of coal dust in mines and indicates application thereof.

investigation of ventilation for vehicular tunnels,[11] a study of friction factors for mine airways,[12] and tests of the strength of mine stoppings constructed of plain concrete.[13]

FACTORS INFLUENCING EXPLOSIBILITY OF COAL-MINE DUST

It was pointed out in Technical Paper 464 that the explosibility of coal dust was not constant, but varied with a number of factors, seven of which could be listed as of primary importance, as they cover all variables commonly met in commercial mines.

These factors are:

1. Size of dust.
   (*a*) Size of coal dust (of primary importance).
   (*b*) Size of rock dust (of secondary importance).
2. Composition of coal dust.
   (*a*) Ratio of volatile to total combustible (of primary importance).
   (*b*) Moisture and ash content (of secondary importance within limits of coals mined in the United States).
3. Presence of inflammable gas in mine passageways.
4. Quantity of dust in passageways.
5. Position of dust with respect to perimeter or cross section of passageway.
6. Source of ignition, its dust raising and igniting power.
7. Surrounding conditions.
   (*a*) Physical condition of the walls of the passageway.
   (*b*) Configuration of the passageways.

Tests detailed in this paper give information on factors 1, 4, 5, and 6. Factors 2 and 3 will be covered in the paper to follow. Information on factor 7 is still too fragmentary to warrant detailed discussion.

SUMMARY OF RESULTS OF EXPLOSIBILITY TESTS

The tests detailed in the following pages fall into four groups, and the conclusions drawn therefrom may be summarized as follows:

EFFECTIVENESS OF ROCK DUSTS OF DIFFERENT SIZE

Tests of mixtures of mine-size (20 percent minus 200-mesh) Pittsburgh coal dust and rock dusts of different size in 1930 indicated that the increased effectiveness of rock dust caused by increasing its minus 200-mesh dust content from 50 to 100 percent was too small to justify additional costs that may accompany fine grinding. In general, it will be cheaper to maintain an additional 2 or 3 percent of the coarser dust permitted by the tentative specifications[14] issued by the Bureau in 1924 and later adopted in essence by the American Engineering Standards Committee.[15] Moreover, there is an advan-

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[11] Fieldner, A. C., and others, Report of U.S. Bureau of Mines to New York State Bridge and Tunnel Commission and the New Jersey Interstate Bridge and Tunnel Commission: Jour. Am. Soc. Heat. and Vent. Eng., vol. 32, 1926; reprint February 1927. See parts 3 and 4, pp. 58–166.

[12] Greenwald, H. P., and McElroy, G. E., Coal-Mine Ventilation Factors: Bull. 285, Bureau of Mines, 1929, 106 pp.

[13] Rice, George S., Greenwald, H. P., Howarth, H. C., and Avins, S., Concrete Stoppings in Coal Mines for Resisting Explosions; Detailed Tests of Typical Stoppings and Strength of Coal as a Buttress: Bull. 345, Bureau of Mines, 1931, 63 pp.

[14] Rice, G. S., Paul, J. W., and Sayers, R. R., Tentative Specifications for Rock Dusting to Prevent Coal-Dust Explosions in Mines: Rept. of Investigations 2606, Bureau of Mines, 1924, 6 pp.

[15] The "Recommended American Practice for Rock-Dusting Coal Mines to Prevent Coal-Dust Explosions", a code approved by the American Standards Association, has been published and discussed in a number of places as follows: Rice, George S., Sayers, R. R., and Harrington, D., Rock Dusting in Coal Mines: Inf. Circ. 6030, Bureau of Mines, 1927, 5 pp. Rice, George S., Effective Rock-Dusting in Coal Mines: Inf. Circ. 6039, Bureau of Mines, 1927, 7 pp. Rice, George S., Safety in Coal Mining (A Handbook): Bull. 277, Bureau of Mines, 1928, pp. 51–53. Rice, George S., Paul, J. W., and Greenwald, H. P., work cited, appendix, pp. 166–168.

tage in having some coarser dust present to lessen caking following moistening.

These tests are described on page 9, and the results are graphed in figure 3. Determination of the size of rock dust most suitable for use in a given mechanical rock-dust distributor or for distribution by air currents in trackless entries or inaccessible workings is a problem to be solved in commercial operations.

TESTS OF DIFFERENT SOURCES OF IGNITION

The term "source of ignition" designates any means by which a coal-dust explosion is initiated. It may be a gas explosion, a blowout shot of explosive, an electric arc, or an open flame. In test work a zone of pure coal dust may be used with any of the above to increase its power and is then considered part of the source. Three standard sources of ignition are in use at the Experimental mine, termed *A*, *B*, and *C*. They are, respectively, the cannon shot of the standard ignition test, the cannon shot and 50-foot zone of pure Pittsburgh coal dust of the standard propagation test, and the 50-foot zone of explosive gas-air mixture of the gas-initiated propagation test. They are described on page 13.

Electric arcs, open lights, and some small inflammations of gas require a preformed dust cloud to initiate a coal-dust explosion. All other sources of ignition are capable of forming the dust cloud that they ignite, provided that the necessary dust is present on the surfaces of the mine passageway. There is no specific relation between the dust-raising and igniting powers of a given group of sources, such as those used in the Experimental mine. Igniting power depends primarily on intensity of flame or heat and dust-raising power on the nature and intensity of the disturbance created in the air in which the dust will be dispersed. The relative igniting and dust-raising power of sources *A*, *B*, and *C* is discussed on page 16.

Effect of varying quantity of dust present.—Formation of a dust cloud will depend on the quantity of dust present as well as on the power of the source of ignition to raise it. Limits of explosibility of mine-size Pittsburgh coal dust were determined in 1931 and 1932 under the three standard test conditions, with the quantity varying over as wide a range as possible. There was a quantity of coal dust (expressed in weight per unit volume of passageway) which gave maximum explosibility with each source, and the greater the dust-raising power of the source, the less was that quantity. The point of maximum explosibility was sharply defined for source *C* but was not so defined for the other two. The results are plotted in figure 5 and discussed on page 17. It is to be expected that the concentration required to give maximum explosibility will vary with the composition of the coal, but the least variation will probably be found with source *C*.

Minimum gas explosion required to ignite coal dust.—Tests[16] were made in 1930 to determine the smallest volume of a uniform gas-air mixture containing 9 to 10 percent natural gas that would initiate an explosion of pulverized Pittsburgh coal dust. The tests are dis-

[16] Rice, G. S., Greenwald, H. P., and Howarth, H. C., Some Experiments on the Initiation of Coal-Dust Explosions by Gas Explosions: Repts. of Investigations 3028, Bureau of Mines, 1930, 9 pp.

cussed on page 25, and their arrangement is illustrated in figure 6. The amount of gas-air mixture required was determined principally by the ease with which a dust cloud could be formed, which depended, in turn, on the manner in which the dust was distributed. One hundred and fifty cubic feet were sufficient when the dust was on overhead shelves that could be overturned by a small force. A smaller amount probably would have sufficed had the dust cloud been preformed by some means. It was necessary to use 300 cubic feet of gas mixture when the dust had to be blown from fixed shelves, and the dust explosion produced had little strength, as it was extinguished after traveling 100 feet by other dust containing 60 percent incombustible material. Use of 500 cubic feet of the mixture initiated an explosion in 100 feet of pure coal dust that continued to the mouth of the mine through dust containing 54 percent incombustible material.

These tests show that small accumulations of gas which might pass unnoticed or be ignored in a commercial mine can be exceedingly dangerous, and, therefore, continuous ventilation must be maintained at all times.[17]

Tests of stratified gas.—Uniform mixtures of fire damp and air are rarely found in coal mines. Usually the gas issuing from coal strata first rises, forming a layer or stratum at the roof and, while diffusing into the air current, makes a zone of explosive mixture near the bottom of the layer. Ignition of this explosive mixture usually results in complete combustion of all the gas as the accompanying disturbance brings additional air into mixture with the gas. Tests of such layers of gas partly confined in pockets in the roof were made in 1930 to determine whether the concussion accompanying their combustion could form a dust cloud that would become ignited and initiate a general dust explosion. The arrangements of the tests are shown in figure 7 and discussed on page 29.

The conditions of test were unsatisfactory, and the work was not carried to conclusion. The layers of gas were ignited without difficulty, but the concussions accompanying their inflammations were too weak to upset cross shelves balanced on narrow supports; hence no dust cloud was formed. Gas issuing from the coal face, floor, or roof strata does form such layers in headings or rooms of gassy or slightly gassy commercial mines when the ventilating current is not sufficient to sweep away the gas, and it issues faster than it can diffuse into the surrounding body of air. If such a layer is disturbed by an increase in ventilation or by movement of men or machinery an explosive mixture is usually formed with the surrounding air, and a greater concussion would accompany combustion of the gas. Conditions would then approach those discussed above. Safety is obtained only by having a sufficient continuous ventilating current to keep the proportion of gas well below the lower explosive limit.

Electric arcs as sources of ignition.—Due to the widely extended use of electricity for mechanical coal cutting, drilling, loading, and haulage electric arcs are now second only to gas explosions as direct initiators of coal-dust explosions in American mines. Their occurrence in clouds of coal dust formed by wreckage of trips of cars

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[17] See Mine Safety Board Decision 9, Recommendations of the United States Bureau of Mines on Certain Questions of Mine Safety, as of Feb. 3, 1933: Inf. Circ. 6732, Bureau of Mines, 1933 (in press).

or by falls of roof has resulted in a number of disasters.[18] A device for demonstrating the ignition of coal dust by an electric arc was first tried at the Experimental mine in 1925, received subsequent improvement in test technique from time to time, and reached its present arrangement in 1930. It now consists of a mine car on which is mounted a piece of trolley wire so that an electric arc is formed between it and the roller bar of the car. A cloud of coal dust is blown onto the arc from a trough mounted on the opposite end of the car. A complete description of the device is given on page 34; figure 10 is a photograph of it, and figure 11 shows it in operation in open air.

An early form of the device was used in 1929 to determine the minimum amount of pulverized Pittsburgh coal dust that would be ignited and produce enough pressure to upset balanced cross shelves loaded with coal dust, with resultant initiation of a general dust explosion. The arrangement of these tests is shown in figure 9, and they are discussed on page 32. It was found that 10 pounds of coal dust were sufficient—a quantity so small in proportion to the weight of dust that would be scattered from a wrecked car of coal, or by a large fall of roof in workings, that it is not surprising explosions have been started in such dust clouds by an electric arc of high amperage from a trolley or power line short-circuited. The arc used in these tests carried only 6.5 amperes with a drop of 65 volts across the electrodes. It is evident that haulageways containing trolley or power wires should be kept thoroughly rock-dusted at all times to prevent the origin of explosions in this manner.[19]

EFFECT OF VARYING DISTRIBUTION OF COAL DUST

A number of tests were made in 1925 and 1926 to determine the effect on the explosibility of coal dust of altering its position with respect to the perimeter of the entry—that is, whether the dust was on the floor, side shelves, or cross shelves. The work was not completed then, and press of other work has prevented resumption since. Detail are given on page 38, and two important qualitative conclusions can be drawn.

A strip of more or less pure coal dust along the floor of an entry, such as may be formed by spillage from cars, is dangerous, as an explosion may travel through it even though the balance of the floor and ribs is properly rock-dusted. Large quantities of rock dust on overhead timbers may be able to prevent this, but experimental proof is lacking. All parts of a roadway must be kept rock-dusted to prevent propagation of an explosion, and spillage of coal should be minimized to reduce contamination of the floor.

The tests showed that a lower percentage of rock dust was needed in the dust on the floor than on the ribs and overhead timbers. This difference can be ascribed to gravity, which aids formation of a cloud from dust on timbers and ledges near the roof and opposes it when the dust is on the floor. Quantitative relations have not been established as yet.

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[18] For a description of some of these disasters see Rice, George S., Safety in Coal Mining (A Handbook): Bull. 277, Bureau of Mines, 1928, p. 80; section headed Explosions Caused by Electric Circuits in Haulageways.

[19] For the recommendations of the Bureau concerning rock dusting see Mine Safety Board, work cited, decision 5.

MISCELLANEOUS TESTS

A few tests were made to determine the effect of small changes in the proportion of minus 200-mesh material in coal dust on its explosibility. A change from 20 to 25 percent had an effect that was appreciable but of no practical importance. This information is of advantage in judging the explosibility of field samples. The tests are detailed on page 43.

Demonstration explosions initiated by blow-out shots near the mouth of the main entry have been made on a number of occasions for groups of visitors. A summary appears on page 44. In late years such demonstrations have been initiated by the device used to demonstrate the ignition of coal dust by an electric arc instead of by a blow-out shot of black blasting powder.

A large number of tests made during the investigation of rock-dust barriers were reported in Bulletin 353.[20] Some information on the explosibility of coal dust obtained from them is included in appropriate sections below.

ALTERATIONS OF EQUIPMENT AND MINE PASSAGES, 1925 TO 1932

Surface.—There were no important changes in the surface equipment of the Experimental mine during the present period. Minor alterations were made as required, and extensive repair work was necessary at some points. Portions of the surface not likely to be needed for test work in the near future are being reforested. A steel tube 12 inches in diameter by 100 feet long was erected just west of the observatory in 1927 and was used in a study of propagation of flame in mixtures of natural gas and air, as described in Technical Paper 427.[21] Descriptions of the remainder of the surface plant in Bulletins 167 [22] and 268 [23] are fairly accurate accounts of conditions at the close of 1932.

Underground.—Extensions of the underground workings can be seen by comparing figures 1 and 2, which give the development in December 1924 and June 1932. Rooms 7 and 8 off no. 1 left butt entry were completed but not cut through to the entry. A new pair of butt entries, termed *A* and *B*, were then started from the air-course nearer the pit mouth to develop the entire tract of unmined coal; eventually they will be over 1,000 feet long. The narrow passageways turned from *B* left butt entry were driven to provide a place for tests of the compressibility and bearing strength of the Pittsburgh coal bed.[24] Use of the gas-initiated propagation test made it necessary to extend the standard test zone to E750 and A750 in 1931, or 200 feet on each entry. Concrete floors were placed, the ribs and roof were gunited, and cross and side shelves were installed. The longer test zone is illustrated in figure 2.

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[20] Rice, George S., Greenwald, H. P., and Howarth, H. C., work cited in footnote 8, appendix, p. 77.

[21] Coward, H. F., and Greenwald, H. P., Propagation of Flame in Mixtures of Natural Gas and Air: Tech. Paper 427, Bureau of Mines, 1928, 28 pp.

[22] Rice, George S., and others, work cited in footnote 6, p. 33.

[23] Rice, George S., Paul, J. W., and Greenwald, H. P., work cited in footnote 7, p. 10.

[24] Greenwald, H. P., Avins, S., and Rice, George S., Compressibility and Bearing Strength of Coal in Place; Tests of Lateral Compression of the Pittsburgh Coal Bed; Tech. Paper 527, Bureau of Mines, 1933, 12 pp.

Instruments.—There were only minor changes in the instruments used for recording the phenomena of dust explosions during the present period. These concerned ease of installation and handling

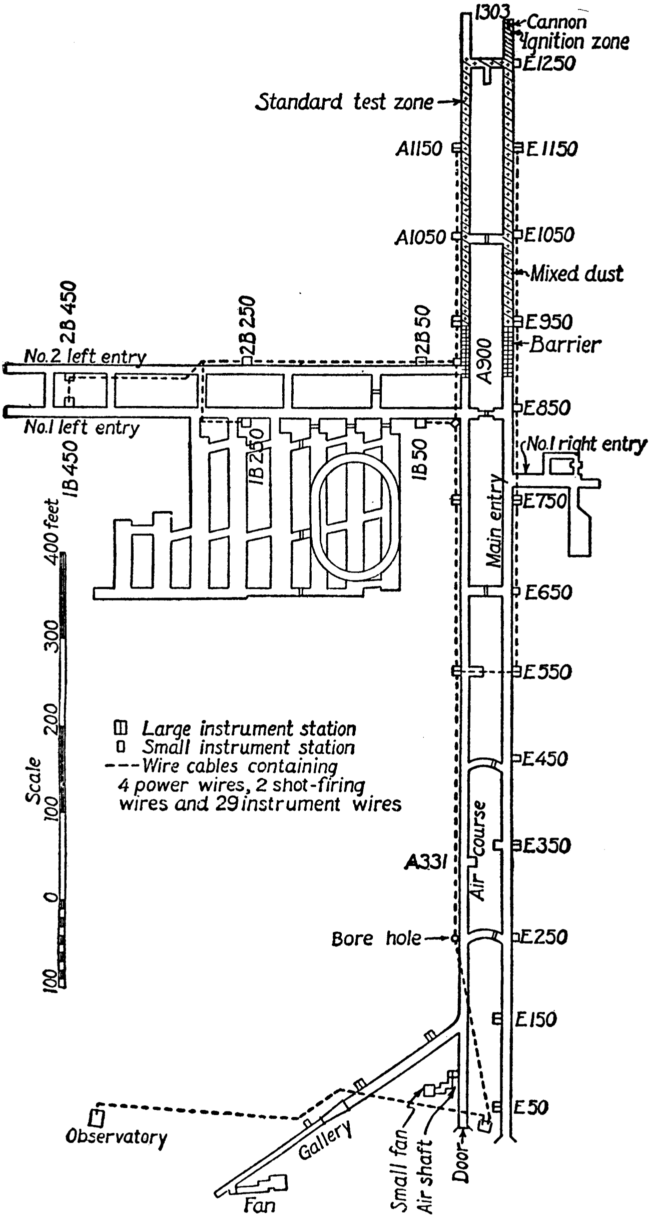

FIGURE 1.—Diagram of Experimental mine, observatory, stations, wiring, and development as of December 1924, showing arrangement of standard propagation test.

during preparation for a test. Full details of the instruments are given in Bulletin 167, page 38, and Bulletin 268, page 13. Further development will be necessary to carry out work planned for the future.

EFFECT OF VARIATION IN CHARACTER OF INERT DUST

In the earlier dusting of commercial mines, rock dust ground locally from strata adjacent to the coal was used predominantly. At a later date limestone dust could be purchased more easily and cheaply in most mining districts, and it came into general use.

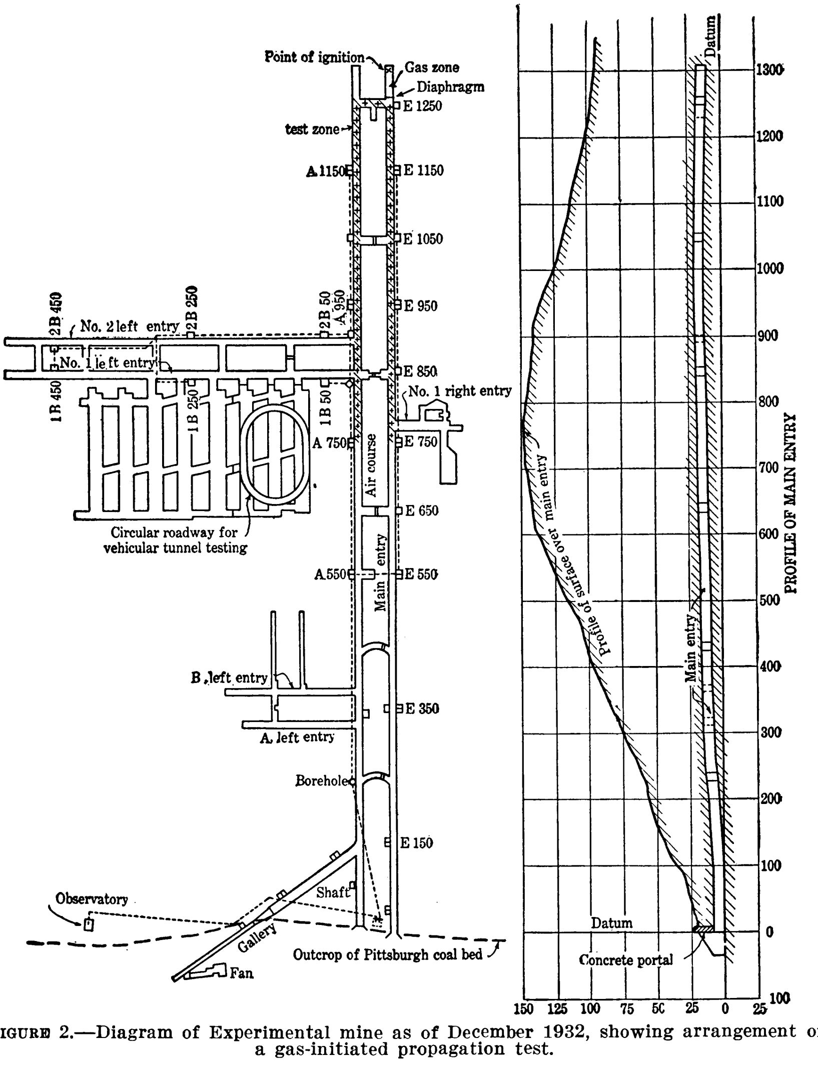

FIGURE 2.—Diagram of Experimental mine as of December 1932, showing arrangement of a gas-initiated propagation test.

Limestone dust is preferable because of its whiteness and freedom from combustible material. Shale dust was used in early Experimental mine tests, and the practice was continued into the present period when limestone dust was substituted.

Results obtained with different inert dusts (rock dusts) to 1929 were summarized in Technical Paper 464.[25] It was concluded that

[25] Rice, George S., and Greenwald, H. P., work cited in footnote 10, p. 5.

variation in size was by far the most important factor. The matter was of practical importance, as some manufacturers were urging that very fine rock dust was superior to that somewhat coarser. Early tests (reported in Bulletin 167, p. 26) had shown that dust containing 95 percent minus 200-mesh material was more effective than dust having only 30 percent, but the difference appeared to be equivalent to a change of about 5 percent in the quantity of incombustible material in the mixture and at that time was not considered of great importance. The matter was taken up again in 1930, and a short series of tests was made with four sizes of rock dust; all passed a 20-mesh sieve, but they contained different proportions of minus 200-mesh material.

TESTS OF DIFFERENT SIZES OF ROCK DUST

TEST METHODS

Standard propagation-test methods were used with no gas in the air current, as illustrated in figure 1. Pittsburgh bed coal dust containing 20 to 22 percent minus 200-mesh material was used in the mixtures; proximate analyses gave 2 percent moisture, 7 percent ash, and a ratio of volatile to total combustible of 0.409.

The coarsest size of inert dust was a yellow shale termed "pit shale" at the Experimental mine.[26] It contained less than 1 percent combustible material. The finer sizes of inert dust were all limestone of a brand sold in large quantities for rock dusting. These dusts contained less than 1.5 percent combustible material, and their sieve analyses were as follows:

Average sieve analyses of inert dusts used

Percent minus	Shale	Limestone		
		Coarse	Intermediate	Fine
20-mesh	94	100		
48-mesh	59	80	100	
100-mesh	41	59	83	100
200-mesh	30	47	68	99

All these samples were "dust" in the sense of the Bureau's definition that coal-mine dust is to be considered as all material passing a 20-mesh sieve. The size of dusts is graded by the proportion thereof passing a 200-mesh sieve. When dusts are prepared by mechanical means, as these were, the size of the coarsest particles becomes smaller as the proportion of minus 200-mesh material increases; this is evidenced in the above table.

RESULTS OF TESTS

Results of all tests applicable to this problem are summarized in table 1. Tests 277 and 317 were made in 1916, tests 495 and 515 in 1919, test 616 in 1923, tests 814 to 817 in 1926, and all tests with higher numbers in 1930.

[26] For a complete description and analysis of this shale see Rice, George S., and others, work cited in footnote 6, p. 150.

TABLE 1.—*Tests of mixtures of mine-size Pittsburgh coal dust and rock dusts of different size*

Test no.	Rock dust used		Incombustible in mixture	Maximum pressures at station 950		Length of flame measured from cannon		Results [2]
	Kind [1]	Proportion minus 200-mesh		Entry	Air course	Entry	Air course	
		Percent	*Percent*	*Lbs./in.*[2]	*Lbs./in.*[2]	*Feet*	*Feet*	
1202	L.	99	54	2	1	350	400	P.
277	S.	96	54	----------	3	350	400	P.
1198	L.	99	59	3	2	125	250	NP.
1193	L.	99	63	1	1	100	175	NP.
616	S.	98	63	1	1	250	325	NP.
816	S.	98	63	1	1	275	375	NP.
317	S.	96	63	2	1	150	200	NP.
1201	L.	68	54	2	2	350	400	P.
1199	L.	68	59	1	1	175	375	NP.
1192	L.	68	63	1	1	125	275	NP.
815	S.	70	63	1	1	150	275	NP.
817	S.	70	68	1	1	125	150	NP.
1200	L.	47	59	4	2	350	400	P.
1191	L.	47	63	----------	2	125	350	NP.
814	S.	46	63	2	2	350	400	P.
495	S.	30	54	3	3	350	400	P.
515	S.	30	54	4	3	350	400	P.
1214	S.	30	63	2	1	250	400	PP.
1213	S.	30	68	1	1	150	150	NP.
1005	S.	36	68	2	2	200	300	NP.

[1] Abbreviations used: L., limestone; and S., shale.
[2] Abbreviations used: P., propagation; NP., nonpropagation; and PP., partial propagation.

The data in columns 3, 4, and 9 of table 1 are plotted in figure 3, incombustible content of the mixture being plotted against the size of rock dust used. The curve shows the limiting mixtures indicated by these tests. As the proportion of minus 200-mesh material in

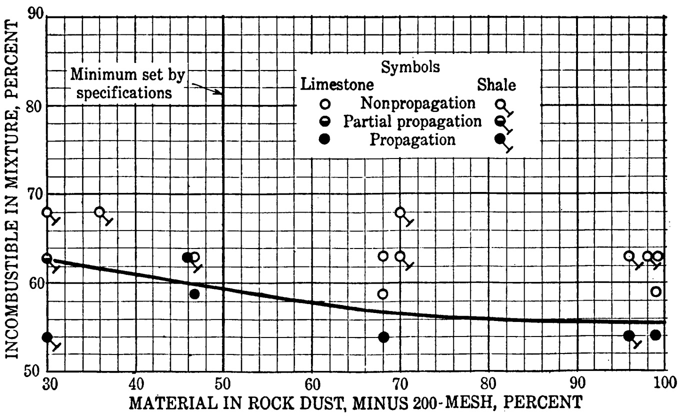

FIGURE 3.—Relative effectiveness of rock dusts of different size in mixtures with mine-size Pittsburgh coal dust.

the rock dust rises from 30 to 50, 70, and 100 percent the curve indicates a decrease in incombustible content of limiting mixtures of mine-size Pittsburgh coal dust from 63 to 59, 56.5, and 55.5 percent. It is evident that the difference in effectiveness between rock dust having 70 and 100 percent minus 200-mesh material is too small to be determined accurately; also the difference between 50 and 100 percent has only limited practical significance. The rock-dusting specifications [27] based on prior testing are fully confirmed by these later tests. It should be noted that these tests determine only the effectiveness of dry dust and give no information as to how the different sizes will behave in mechanical rock-dusting machines, or concerning their relative liability to cake when wetted and dried.

There is one discrepancy in the results of the tests in table 1. Tests 1191 and 814 were duplicates, except that limestone was used in the former and shale in the latter. The result was propagation in test 814 and nonpropagation in 1191. The cause of this difference is not known, but the error is believed to be in test 814 as use of much coarser shale in test 1214 resulted only in partial propagation. The result of test 814 has been ignored in forming the curve of figure 3.

Additional data from ignition tests.—Correlation of results of ignition tests with mixtures of mine-size Pittsburgh coal dust and inert dusts of different size shows that the above relations hold exactly only when the source of ignition has enough dust-raising power to disperse the coarser inert dust properly. These ignition tests were made at widely separated periods with different ends in view. When the inert dust was shale containing 30 percent minus 200-mesh material and the mixture was placed at the rate of 1 pound of coal dust per linear foot of entry, the limiting mixture had an incombustible content between 36 and 40 percent (see p. 39, tests 520 and 517, Bulletin 268). Changing the inert dust to limestone containing 70 percent minus 200-mesh material reduced the incombustible content of the limiting mixture to a point between 22 and 26 percent, a decrease of 14 percent (see tests 1292 and 1291, table 2, this paper). A similar change at a loading of 2 pounds per linear foot reduced the incombustible content of the limiting mixture from approximately 50 to 35 percent (compare tests 349 and 316, p. 207, Bulletin 167, with tests 1303 and 1310, table 2, this paper).

These results are important, as they indicate that the blow-out shot used as a source of ignition in standard ignition tests does not have sufficient dust-raising power to disperse the coarser inert dust properly. The more violent source of ignition used in standard propagation tests does so more completely.

SUMMARY [28]

To summarize, the tests show that rock dust should contain 50 or more percent minus 200-mesh material, but the difference between dusts containing 50 and 100 percent minus 200-mesh size is not enough to have great practical importance in rock-dusting commercial mines, so far as power to quench an incipient explosion is concerned. As a result of these tests it was decided that in future limestone dust of ordinary commercial size containing about 70 percent minus 200-mesh material would be used in the test work both as a

[27] For references to the rock-dusting specifications see footnote 15.

[28] A summary of these tests was first published as a report of investigations. See Rice, G. S., Greenwald, H. P., and Howarth, H. C., The Effectiveness of Different-Size Rock Dusts in Preventing Coal-Dust Explosions in Mines: Rept. of Investigations 3034, Bureau of Mines, 1930, 10 pp.

matter of convenience and to lessen experimental errors in determining limits of explosibility of different coal dusts. This will necessitate the use of small correction factors when results obtained with the finer rock dust are compared with those obtained previously.

OTHER CHARACTERISTICS OF ROCK DUST

Composition.—Results of early tests with inert dusts of different compositions were reported in Bulletin 167, page 141. All data available in 1929 were summarized in Technical Paper 464, page 5. There has been no additional experimental work since Technical Paper 464 was issued. The tentative conclusion then drawn was that change of composition of inert dust unaccompanied by a change in physical character did not alter its power to extinguish coal-dust explosions so long as there was not more than 2 percent combustible material in it. This limit on combustible material was set for experimental purposes; rock-dusting specifications permit a maximum of 5 percent.

It has been suggested at different times that gypsum would have special advantages as a rock dust because additional heat would be absorbed in liberating the combined water it contains. The Safety in Mines Research Board of Great Britain has reported experimental confirmation of this superiority in its regular communications to the Bureau of Mines. However, this advantage is offset by a tendency to cake when moistened, and it is inadvisable to use it in those mines which generally have a moist atmosphere.

To reduce the causation of pulmonary diseases among miners the Bureau recommends tentatively that rock dust contain less than 25 percent free silica. Physiological tests have indicated that silicates may be harmful also. The effect of breathing silica and silicate dust is receiving much attention in various laboratory studies, but no final pronouncement has been made as to the limiting percentage that may be permitted in rock-dusting material.

Specific gravity.—Gallery tests reported in Technical Paper 464, page 6, indicate that the apparent density of a rock dust has minor importance in determining its effectiveness in preventing propagation of an explosion. The weight of rock dust present and not the volume determines its effectiveness. On a weight basis diatomite (kieselguhr) dust, whose volume per unit weight is 4 to 6 times that of limestone and shale, was but slightly more effective in extinguishing explosions. A dust of low apparent density will be raised more readily to form a cloud, but the forces operating in propagation tests in the Experimental mine are sufficient to raise the heavier limestone and shale dusts, and low density then has little importance. Results are different when the dust is used in barriers.[29] There a compact mass of dust must be dispersed rapidly and the diatomite is more effective. The use of this almost pure silica dust in barriers is not objectionable from a health standpoint, as it is not dispersed in the mine air except in an explosion.

Color.—The color of rock dust has no bearing on its effectiveness in extinguishing flame, but it is desirable that it be white or light colored so that continued deposition of coal dust during mining can be estimated by inspection. White dust improves illumination

[29] Rice, George S., Greenwald, H. P., and Howarth, H. C., work cited in footnote 8, pp. 50–52.

and therefore tends to reduce other types of mine accidents caused by poor lighting. Dark color may indicate the presence of combustible material in a mine dust and a dark dust should be regarded with suspicion until its composition is known.

TESTS OF DIFFERENT SOURCES OF IGNITION

"Source of ignition" is listed on page 2 as a major factor influencing the explosibility of coal dust. A source usually forms the dust cloud that it ignites, but there are exceptions, such as electric arcs and open flames. It is necessary, therefore, to distinguish between dust-raising and igniting powers, and there is no fixed relation between them as one alters the source.

The sources of ignition used most commonly in the Experimental mine are those of the standard ignition, standard propagation, and gas-initiated propagation tests, which have been termed *A*, *B*, and *C*, respectively. Standard ignition and propagation-test methods were described in detail in Bulletin 167, pages 179–186, and more briefly in Bulletin 268, pages 35–36. The gas-initiated propagation test was developed during the present period and differs from the standard propagation test in two respects. The source of ignition is a gas explosion (source *C*) instead of a cannon shot augmented by pulverized Pittsburgh coal dust (source *B*), and the test zone extends 200 feet farther on each entry to E750 and A750. Arrangements of standard propagation and gas-initiated propagation tests are illustrated in figures 1 and 2, respectively.

STANDARD SOURCES OF IGNITION

DESCRIPTION

Source A.—This is a blow-out shot of 4 pounds of FFF black blasting powder tamped in a steel cannon with 3 pounds of slightly damp clay or shale stemming. The cannon is 24 inches in diameter by 36 inches in length with a bore 2.25 inches in diameter by 21.5 inches in length chambered at the rear. It is placed in the center of the roadway at the face of the main entry, so that flame is projected outward along that entry. The face is 50 feet in advance of the open crosscut leading to the air course.

Source B.—The blow-out shot of source *A* is used, to which are added 100 pounds of pulverized Pittsburgh coal dust distributed from the cannon to the inby corner of the open crosscut. Approximately 50 pounds of this dust are distributed on side shelves extending throughout the zone and one cross shelf at its outer end. Twenty-five pounds are distributed over a space 3.5 feet wide and 16 feet long immediately in front of the cannon, and the remaining 25 pounds are scattered over the balance of the floor.

Source C.—A uniform mixture of natural gas and air containing 9 to 9.5 percent gas is confined in the dead end of the main entry by a paper diaphragm erected immediately inby the open crosscut. The enclosed volume is approximately 2,700 cubic feet. The mixture is ignited by firing into it a black powder igniter fastened midway between roof and floor to a post erected 8 feet from the face. Ignition close to the face gives the greatest dust-raising power in the dust zone outby.

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PROPERTIFS

RESULTS OF TESTS

Length of flame.—The length of flame of source *A* is 25 feet. This has been reported previously and was confirmed by tests 761 to 768, 953, 1064, and 1065 made during the present period with the primary intention of determining the sensitivity of barriers.

Source *B* projects flame to E1200 and A1250, points which are 50 feet beyond the original confines of the coal dust used in the source. Extension of flame beyond the source is therefore twice the length of the ignition zone. This was also reported previously and confirmed by tests 953 and 963 in the present period.

Source *C* was used alone in tests 917, 981, and 1273. In test 917 flame extended to E1175 and A1200; in the others it extended to E1175 and A1225. The extension of flame beyond the gas zone was 3 to 3.5 times the length thereof. When source *C* was being developed in 1925 three igniters were used to initiate the gas explosion instead of one, and it was found that this did not give a longer flame but did give a higher pressure, as will be noted. Placing mine-size coal dust in the gas zone had no effect on flame length, and it is assumed that the rapid combustion of the gas consumed all the oxygen before the coal dust could form a cloud and enter into the reaction. On the other hand, 200 pounds of coal dust immediately outby the gas zone caused considerable extension of flame and increase of pressure. Shale dust on the side and cross shelves immediately outby the gas zone caused marked reduction in the flame extension. Gas in the air current extended the flame of source *C*; flame reached E1125 and A1200 with 1.2 percent gas and E1125 and A1150 with 2.2 percent. The extensions of flame beyond the original gas zone were 4.5 and 5.5 times the length thereof in these respective cases.

The Safety in Mines Research Board of Great Britain has conducted experiments on the projection of flame beyond the confines of an explosive gas-air mixture in the laboratory and in a steel tube 7.5 feet in diameter.[30] There was no side opening in the tubes corresponding to the open crosscut connecting the main entry and air course in the Experimental mine. When a mixture of about the composition used in source *C* was tested in the laboratory apparatus it was found that the projected flame was 5 to 6 times the length of the gas mixture itself. The similar ratio of projection was 4 to 4.5 when the 7.5-foot-diameter tube was used. The difference was ascribed to loss of pressure at the shutter, which confined the gas mixture during preparation and which was withdrawn through the side of the gallery, the slide for it not being tight. The still lower ratios (3 to 3.5) obtained in the Experimental mine are doubtless due to branching of the passageway at the point where the flame issues from the space in which the gas mixture is confined.

Pressure.—Typical pressure records at E1258 (the inner edge of the open crosscut) given by the three sources of ignition with dustless zones outby are plotted in figure 4. The first indication of

[30] Burgess, M. J., Firedamp Explosions; The Projection of Flame, pt. I: Safety in Mines Research Board Paper 27, 1926, 14 pp.
Burgess, M. J., Firedamp Explosions; The Projection of Flame, pt. II: Safety in Mines Research Board Paper 42, 1928, 8 pp.

pressure on each record has been taken as zero time. Dotted portions of the curves indicate periods when the manometer diaphragm was in more or less violent vibration, so the record is unreliable. The first 0.1 second of the records given by sources *A* and *B* are similar and may be attributed to the blow-out shot directly. Beyond this point the record of source *A* is irregular but always close to zero pressure and is probably caused mainly by the pressure waves initiated in the first 0.1 second and subsequently reflected from the various surfaces of the passageways. With source *B* there is a rise in pressure during the time interval 0.17 to 0.22 second after discharge of the cannon, during which flame is present, and the heat of the flame is probably primarily responsible for the pressure rise. After the flame record ends the pressure falls slowly and irregularly.

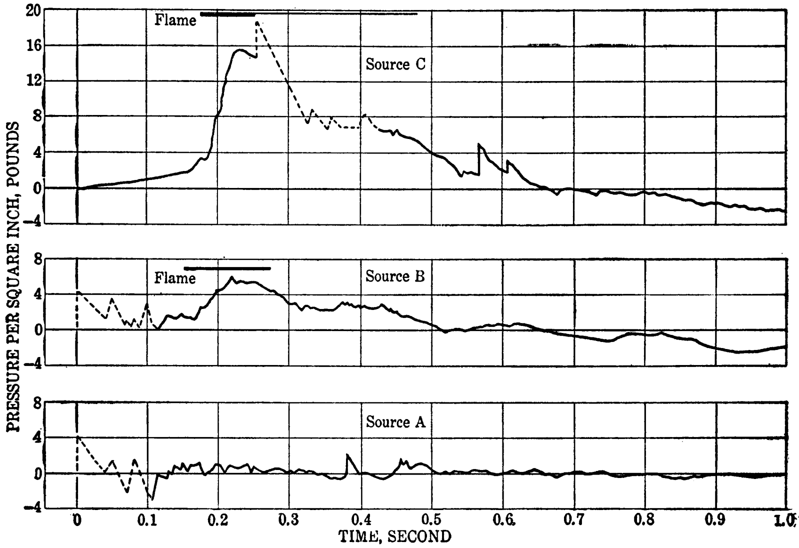

FIGURE 4.—Pressure records obtained at station E1258 from standard source of ignition.

The record for source *C* is of an entirely different type. There is no initial concussion, and the pressure rises gradually to about 2 pounds just before flame appears on the film record, then increases suddenly to about 16 pounds, and a vibratory period ensues during which the pressure falls. A flame of low actinic power is present during this period. After this, the pressure falls irregularly, and strong reflected waves appear.

The pressures shown in figure 4 travel as waves, and the records are repeated on succeeding manometers with modifications caused by attenuation of the waves as they travel. Source *C* produces nearly as great a pressure at station E1150 as at E1258, which is doubtless connected with the fact that flame comes within 25 feet of the former station. Station E1258 was constructed about the middle of the present period, and the following statements apply to pressures produced by source *C* and recorded at E1150. Use of 3 igniters to start the gas explosion instead of 1 resulted in a 4-pound increase in pressure but no greater flame length. Mine-size coal dust in the zone with the gas caused no change in recorded pressure, but 200 pounds of it immediately outby the gas zone caused an 8-pound increase. Up to 2.2 percent gas in the air current in a dustless zone beyond the explosive mixture gave no certain increase in pressure, although it did extend the flame. Shale dust placed on cross and side shelves immediately outby the gas zone and in the absence of coal dust caused a slight reduction in pressure but shortened the flame considerably.

IGNITING POWER

Theoretically one might seek to measure the igniting power of a source by determining the weight of a given dust cloud that it brought to ignition temperature in unit time. Such measurements would be difficult in any apparatus and are impossible in the Experimental mine. They would have to be made at the point where the source was igniting the dust cloud; that is, in the inner 25 feet of the main entry for source *A* and at the junction of the main entry and the open crosscut for sources *B* and *C*. Heat produced at a distance from the actual point of ignition has an effect only as it is transferred to or prevents escape of other heat from that point by conduction, convection, and radiation. The rate of production of heat at the time the flame of the source impinges on the dust cloud to be ignited is an important and, at present, unmeasurable factor. Total heat liberated will play some part, particularly in connection with losses to surrounding walls.

With certain assumptions it can be computed that the total heat liberated by sources *A*, *B*, and *C* is 5,700, 290,000, and 250,000 B.t.u., respectively.[31] With source *A* the initial rate of liberation of heat is high and probably decreases rapidly. With source *B* burning of the coal dust will probably retard or prevent this decrease and there may be an increase finally. With source *C* the initial rate is very low, increases rapidly, and one can surmise that it will be higher than that of source *B* at the end of the flame travel through the source of ignition, but there are no definite data. In general, one would expect that source *B* had much greater igniting power than source *A* and source *C* might be superior to *B*. Tests of Pittsburgh coal dust (discussed below) have shown that highest explosibility is found with source *C*, slightly lower with source *B*, and considerably lower with source *A*. If one can assume some connection between limit of explosibility and igniting power of the source under Experimental mine test conditions these results are harmonious.

DUST-RAISING POWER

The ability of a source of ignition to form a dust cloud depends on the disturbance created in the air in which the dust is to be dispersed. If the dust lies on a rigid surface it is moved either by violent eddying of the air close to it or by a change in pressure which permits expansion of the air in the dust layer, with resultant

[31] The computation for source *A* is based on determinations of the calorific value of black blasting powder reported by Hall, Clarence, Snelling, W. O., and Howell, S. P., Investigations of Explosives Used in Coal Mines: Bull. 15, Bureau of Mines, 1911, p. 176. The value for source *A* is also basic for source *B*, to which is added the heat produced by combustion of Pittsburgh coal dust with all the oxygen contained in the dead end of the main entry under normal temperature and pressure, the products being carbon dioxide and water. For source *C* the combustion of an equal volume of oxygen by the natural gas is assumed.

projection of the dust from its resting place. It follows that the source which produces most violent air movement and most rapid changes in pressure will have greatest dust-raising power.

The manometer curves of figure 4 are, at present, the only means by which the dust-raising power of sources *A*, *B*, and *C* can be compared. Consideration may be directed first to the raising of dust at the point where primary ignition thereof occurs. With source *A* this occurs in the first 25 feet outby the cannon, 25 to 50 feet inby the point where the manometer record was obtained. It is evident that the dust is raised by the concussion accompanying the blow-out shot, and this is represented by the first 0.1 second of the manometer record.

Primary ignition of dust in the test zone by sources *B* and *C* occurs at the junction of the main entry and the open crosscut, the point at which the manometer records were taken. With source *B*, flame arrived at this point 0.16 second after the first pressure wave in the air, and most of the disturbance during this period was caused by the cannon shot. The additional disturbance occurring during the flame period would assist in dispersing the dust and aid the spread of flame throughout the cross section of the entry. When source *C* is used, the disturbance which precedes the flame has little, if any, greater dust-rising power than that which precedes the flame of source *B*. Much greater dust-raising power resides in the front of the flame of source *C*, and conditions are evidently much more favorable to formation of a uniform dust cloud at the moment of ignition than when source *B* is used.

Conditions are altered after the primary ignition of the dust under test. The pressure waves recorded in figure 4 continue along the passageways with the velocity of sound under the conditions then and there obtaining. If the dust mixture is near the limit of explosibility (as is the case in most tests), the flame suffers a check and the pressure waves which accompanied it pass on ahead of it. They then form the dust cloud through which the flame will travel, if the dust is of explosive character, and it is evident that source *C* will form the best dust cloud and source *A* the poorest. Gravity tends to destroy the dust cloud continually but may be a negligible factor because of the shortness of the time; there is no direct evidence on this, however. One would expect it to be most effective with source *A* and least effective with source *C*.

The general conclusion is that the dust-raising power of source *C* is much greater than that of source *B* which, in turn, is decidedly superior to that of source *A*. This conclusion is confirmed by the results of the following tests.

TESTS OF MINE-SIZE PITTSBURGH COAL DUST, CONCENTRATION VARYING

PREVIOUS WORK

The effect of varying the quantity of coal dust placed in the test zone in the Experimental mine was investigated first in 1917.[32] Standard propagation-test methods were used, and more tests were made of pulverized dust than of other sizes. Explosibility of this

[32] Rice, George S., and others, work cited in footnote 6, pp. 213–217, and fig. 33, p. 205.

size increased rapidly to a dust loading of 0.133 ounce per cubic foot, at which point there was some indication of a maximum. Concerning this, Bulletin 167 says on page 215:

It will be noted in figure 33 that only with the pulverized dust (100-mesh dust, 75 percent of which would pass through 200-mesh) was propagation obtained with any one loading of coal dust where propagation could not be obtained through the same coal-dust and shale-dust mixture with a different distribution. The instance referred to is the one in which propagation was obtained through a mixture of 75 percent pulverized shale dust and 25 percent coal dust, distributed at the rate of 1 pound of coal dust per foot, but was not obtained through the same mixture with different weights of dust distributed. Too much weight should not be attached to the one test in which an explosion resulted, because propagation was not obtained through the same mixture with nearly the same weight of coal dust distributed (1¼ pounds per foot) in several tests with pulverized dust. Also in test 300, with one half pound of dust distributed, propagation was almost obtained. Therefore the liability of obtaining an explosion through mixtures of 75 percent shale dust and 25 percent coal dust is probably nearly the same with dust distributions corresponding to rates of one half to 2 pounds of coal dust per foot.

The investigators of the Safety in Mines Research Board of Great Britain conducted similar experiments with an English coal in a steel gallery in 1929 and reported their findings in Paper 64.[33] An "optimum" concentration [34a] was found at which explosibility was a maximum, but the decrease at higher concentrations was not large. Under the cooperative agreement these results were available to the Bureau before they were published, and it was evident that they should be confirmed by tests under the different conditions existing in the Experimental mine. This work was started in April 1930 and completed in April 1932, a total of 78 tests being made.

ARRANGEMENT OF TESTS

Mine-size coal dust was used, and the inert dust was limestone containing 64 to 68 percent of minus 200-mesh material. The concentration of coal dust was varied from the minimum that would give an explosion with no admixed limestone to the maximum that could be placed on the shelves. This maximum was 6 pounds of mixed dust per linear foot (1.6 ounces per cubic foot), and the concentration of coal dust then depended on the proportion thereof in the mixture. The dust was divided equally between cross shelves, side shelves, and the floor. The results were correlated on the basis of weight of coal dust per unit volume present. One pound of dust per linear foot equals 0.267 ounce per cubic foot or 267 grams per cubic meter.

Complete series of tests were made with sources *C*, *B*, and *A*. With source *A* there were two methods of placing the mixed dust in the first 50 feet outby the cannon, termed loadings 1 and 2. With loading 1 the rate of distribution of dust in this space was twice that used outby; with loading 2 there were always 100 pounds of

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[33] Mason, T. N., and Wheeler, R. V., The Inflammation of Coal Dusts; The Effect of the Presence of Firedamp: Safety in Mines Research Board of Great Britain Paper 64, 1931, pp. 5–8.

[33a] The term "concentration" of dust used in the British publication cited and as employed in this bulletin means the amount of dust loaded or distributed per unit of volume in the respective test zone of the gallery or mine entry. Not all this dust may be in the air at the moment of passage of flame. The concentration of a dust mixture in a given space may be more or may be less than is required for combination with all the oxygen of the air in that space under the pressure existing at the moment of explosive combustion.

coal dust in this space plus whatever limestone dust was in the mixture under test. These two loadings are identical at 0.267 ounce per cubic foot (1 pound per linear foot). Correlation of results was on the basis of concentration outby the dead end.

RESULTS AND DISCUSSION

Primary results of the tests are given in table 2. The tests are grouped according to the source of ignition used, with subarrangement according to increasing quantity of dust present and incombustible content of the mixture.

TABLE 2.—*Tests of mine-size Pittsburgh coal dust with quantity and sources of ignition varying*

1. INITIATION BY SOURCE *C*[1]

Test No.	Quantity of coal dust	Incombustible in mixture	Maximum pressure from dust		Length of flame measured from E1300		Result[2]
			E950	A950	Entry	Aircourse	
	Oz. per cu. ft.	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Feet*	*Feet*	
1252	0.040	7	3	3	225	300	NP.
1256	.053	7	3	3	200	275	NP.
1257	.067	7	3	3	300	325	NP.
1255	.067	44	2	3	275	300	NP.
1254	.067	48			225	350	NP.
1251	.067	53	3	3	225	250	NP.
1258	.080	7	5	5	425	375	NP.
1259	.093	7	17	14	550	600	P.
1260	.113	53	6	5	425	600	PP.
1261	.133	67	5	3	275	600	PP.
1262	.133	72	4	3	225	325	NP.
1272	.160	68	3	3	325	200	NP.
1268	.200	63	6	4	550	600	P.
1263	.200	67	4	3	250	400	NP.
1267	.267	58	6	5	550	600	P.
1266	.267	63	3	3	350	225	NP.
1240	.267	67	3	2	250	275	NP.
1239	.267	72	3	2	150	200	NP.
1270	.400	54	4	4	550	600	P.
1269	.400	58	3	3	375	225	NP.
1274	.533	50	5	4	550	200	PP.
1271	.533	55	3	3	350	200	NP.
1245	.533	63	3	3	275	200	NP.
1276	.800	41	3	3	550	425	PP.
1283	1.067	36	22	9	550	425	PP.
1277	1.600	10		62	550	600	P.
2. INITIATION BY SOURCE *B*							
1275	0.105	10	6	4	325	400	PP.
1238	.133	46	2	2	250	400	PP.
1218	.133	54			175	350	NP.
1220	.200	50	4	4	350	400	P.
1219	.200	54	1	1	175	325	NP.
1217	.200	59	1	1	175	200	NP.
1201	.267	54	2	2	350	400	P.
1199	.267	59	1	1	175	375	NP.
1216	.333	59	1	1	300	250	NP.
1236	.400	54	3	3	350	400	P.
1215	.400	59	1	1	175	200	NP.
1235	.533	59	2	2	325	400	PP.
1287	.667	53	1	2	350	400	P.
1284	.733	58	2	2	125	150	NP.
1285	.800	54	3	2	175	225	NP.
1286	.880	48	3	3	350	400	P.

[1] Percentage of gas in dead end of main entry was 9.0 to 9.5 in all except the following tests: 1254, 8. percent; 1266, 8.8 percent; 1271, 8.4 percent; 1276, 8.1 percent.

[2] Abbreviations used: P., propagation; PP., partial propagation; NP., nonpropagation; I., ignition; PI., partial ignition; and NI., nonignition.

TABLE 2.—*Tests of mine-size Pittsburgh coal dust with quantity and sources of ignition varying*—Continued

3. INITIATION BY SOURCE *A*, LOADING 1[3]

Test No.	Quantity of coal dust	Incombustible in mixture	Maximum pressure from dust		Length of flame measured from E1300		Result
			E950	A950	Entry	Aircourse	
	Oz. per cu. ft.	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Feet*	*Feet*	
1278	0.120	9	3	----------	225	400	PI.
1297	.200	17	2	3	350	400	I.
1296	.200	22	1	1	225	275	NI.
1292[4]	.267	22	7	7	350	400	I.
1291[4]	.267	26	1	1	175	300	NI.
1290[4]	.267	31	1	1	75	175	NI.
1289[4]	.267	35	1	1	100	125	NI.
1298	.400	27	6	5	350	400	I.
1299	.400	32	1	1	175	250	NI.
1305	.533	31	14	12	350	400	I.
1306	.533	35	1	2	350	400	I.
1307	.533	40	1	1	175	275	NI.
1302	.667	27	30	22	350	400	I.
1301	.667	32	1	1	175	300	NI.

4. INITIATION BY SOURCE *A*, LOADING 2[5]

Test No.	Quantity of coal dust	Incombustible in mixture	E950	A950	Entry	Aircourse	Result
1293	0.200	17	1	----------	350	400	I.
1295	.200	26	1	1	125	250	NI.
1294	.220	22	2	4	350	400	I.
1311	.400	29	9	9	350	400	I.
1312	.400	33	2	1	325	325	NI.
1313	.400	38	1	1	50	100	NI.
1303	.533	32	2	3	350	400	I.
1310	.533	38	1	1	100	175	NI.
1304	.667	32	8	17	350	400	I.
1314	.667	38	1	1	175	250	NI.
1315	.800	33	11	9	350	400	I.
1320	.800	39	3	3	350	400	I.
1321	.800	43	1	1	175	250	NI.
1316	.933	33	----------	6	350	400	I.
1322	.933	43	1	1	125	175	NI.
1317	1.067	33	12	10	350	400	I.
1318	1.067	38	3	2	350	400	I.
1319	1.067	43	1	1	100	175	I.

[3] Mixed dust loaded to cannon. Coal dust in mixture in first 50 feet placed at double the rate used in balance of zone and given in second column.

[4] This test can be placed in either part 3 or 4 as the 2 methods of loading are identical at 0.267 ounce per cubic foot.

[5] Mixed dust loaded to cannon. Coal dust in mixture in first 50 feet placed at rate of 0.267 ounce per cubic foot in all tests. Loading outby given in column 2.

LIMITS OF EXPLOSIBILITY

Those tests in table 2 which are of primary importance in determining limits of explosibility are plotted in figure 5, and curves are drawn for the three sources.

Source C.—With source *C* the lower limit of explosibility of pure mine-size coal dust lies between 0.080 and 0.093 ounce per cubic foot, and 0.085 ounce may be taken as a fair average value. The curve rises rapidly to a maximum of 67 percent incombustible at 0.125 ounce, and this is closely the quantity of coal dust required to consume all the oxygen of the air to carbon dioxide and water, the air being taken at normal temperature and pressure. Following this, there is a linear fall of explosibility with increasing concentration to about 0.5 ounce, after which the rate of fall decreases and the curve tends to become horizontal. Beyond 0.5 ounce the curve is determined entirely by three tests, nos. 1274, 1276, and 1283, in all of which the result was partial propagation. It is possible that additional work would cause some alteration in the curve in this range; one would expect the change to be toward higher explosibility, but it appears unlikely that the increase would be more than 5 percent incombustible at a concentration of 1.0 ounce.

The results obtained in the early stages of this work raised the hope that the straight-line decrease in explosibility would continue until the composition of pure coal dust was reached, and test 1277 was made with pure coal dust placed at the rate of 1.6 ounces to determine the matter. A violent explosion resulted, and the curve evidently lay much higher at this concentration, but the subsequent determination of its position could not be carried beyond 1.067 ounces

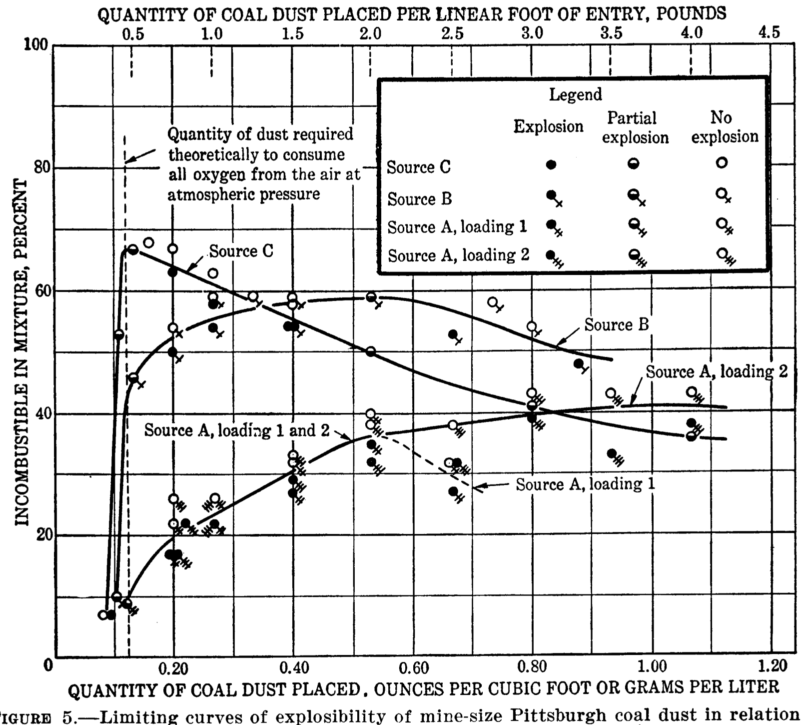

FIGURE 5.—Limiting curves of explosibility of mine-size Pittsburgh coal dust in relation to quantity present, initiation by sources *C*, *B*, and *A*.

because the requisite quantity of dust could not be placed on the shelves. It appears improbable that the curve will show any additional fall of importance at higher concentrations.

Source B.—With source *B* the lower limit of explosibility of pure mine-size Pittsburgh coal dust is about 0.105 ounce, an increase of 25 percent over that obtained with source *C*. The curve rises rapidly at first but has a long, flat top in contradistinction to the sharp peak obtained with source *C*. Maximum explosibility has been placed at 0.53 ounce in deference to the result (partial propagation) of test 1235. From the practical standpoint the variation in explosibility between 0.3 and 0.6 ounce is negligible. Beyond 0.6 ounce explosibility decreases considerably but evidently tends to become constant at high concentrations.

Source A.—A single curve has been drawn for both loadings 1 and 2 of source *A* up to a concentration of 0.53 ounce. Strictly there should be two curves, but their maximum divergence is about 3 percent incombustible and not more than the error of duplicate experiments when this source is used. An average curve is justified under these conditions. The lower limit of explosibility of pure mine-size Pittsburgh coal dust is about 0.120 ounce, or 40 percent greater than was obtained with source *C*. Beyond a concentration of 0.53 ounce the curves for loadings 1 and 2 diverge sharply. The curve for loading 1 falls. This is ascribed to the retarding or "superdusting" effect of the large quantity of dust immediately in front of the cannon as discussed in Bulletin 167, page 95. It is probable that this curve will bend and become horizontal, but experiments to prove it could not be made as the requisite quantity of dust could not be placed.

The curve for loading 2 continues to rise at least to a concentration of 1.0 ounce and may continue to rise for higher concentrations, but larger quantities of dust could not be used. Comparison of the curves for loadings 1 and 2 makes it evident that the quantity of dust immediately in front of the cannon is an important factor when source *A* is used.

COMPARISON OF LIMITS

Dust-raising power.—The wide variations in explosibility shown by the curves of figure 5 are evidently connected with the igniting and dust-raising powers of the sources of ignition used, as there were no other variables in the test work as plotted. Assuming a dust cloud of uniform and unchanging concentration during an explosion one would expect a lower limit of inflammability of pure dust, maximum explosibility at or near the concentration of coal dust using all the oxygen of the air, and continued decrease in explosibility as larger quantities of dust were introduced. The last follows from the fact that the excess coal dust would absorb heat. Theoretically there should be an upper as well as a lower limit of explosibility for pure coal dust. The curve for source *C* agrees with the above theory up to a concentration of 0.5 ounce. Beyond this point one can assume that the source can no longer disperse properly all the dust present, and the quantity that is effective approaches a constant value. The lesser dust-raising powers of sources *B* and *A* are evident from the fact that 4 and 8 times as much dust must be present, respectively, to give maximum explosibility. The quantity of oxygen in the air is the governing factor, and one may postulate that at maximum explosibility [34] the quantity of dust actually in the air is approximately the same for all three sources; that is, the total quantity of coal dust required to be present to give maximum explosibility is an inverse function of the dust-raising power of the source of ignition.

The above holds only as long as the dust-raising power of the source of ignition predominates over that of the explosion itself. When dust mixtures that are near the limit of explosibility are used, this condition is certainly fulfilled for source *C*, and probably

[34] It should be remembered that "maximum explosibility" refers to the capacity of the dust to propagate an explosion and not to the maximum violence that it can cause in an explosion. The two are not necessarily related.

is for source *B*, but for source *A* there may be some doubt. This applies within the length of the test zones used in the Experimental mine, which are short enough to prevent gravity greatly interfering with the dust cloud produced by the pressure waves originated by the source of ignition and traveling ahead of the flame of the explosion. Here again source *C* will be least and source *A* most affected. One can postulate a case, such as evidently occurs in an extensive explosion in a commercial mine, in which the zones are so long that the original dust cloud in the outer portions thereof is dissipated before the flame arrives and the explosion forms its own dust cloud as it advances. In such an instance the concentration of dust giving maximum explosibility in any zone would depend on the dust-raising power of the explosion itself in that zone, and the source of ignition would have no influence.

Igniting power.—If one assumes constant conditions of dust-cloud formation and dissipation of heat to the surroundings the quantity of incombustible dust required in a mixture to prevent propagation of a coal-dust explosion will depend largely on the rate at which heat is liberated by combustion of the coal dust. This derives from the fact that the incombustible acts primarily to absorb this heat and reduce the temperature below the igniting point of the coal dust. It follows that the amount of incombustible dust required (which is taken as a measure of explosibility) will be related to the igniting power of the source of ignition, at least in the early stages of an explosion, for an increase in igniting power will be accompanied by an increase in the rate of liberation of heat from the burning coal dust, and more incombustible dust must then be used to absorb this heat and prevent continued propagation. It was stated above that one would expect source *C* to have the greatest and source *A* the least igniting power. The curves of figure 5 agree with this; the maximum limits of inflammability for mine-size Pittsburgh coal dust are 67, 59, and 41 percent incombustible, respectively, for sources *C*, *B*, and *A*.

It may be argued that the foregoing hypothesis can hold only in the neighborhood of the point where the coal dust is actually ignited and beyond that region the explosion would develop an igniting power of its own. The maximum explosibilities shown by figure 5 could not then be directly related to the igniting power of the sources, for they are determined in part by the flame traveling to the ends of the test zone, a distance 3.5 to 4.4 times the length of flame obtained from sources *B* and *C* in dustless zones. In opposition to this it may be reasoned that continuation of the explosion depends on maintenance of a temperature equal to or greater than the temperature of ignition of the coal dust under test. Maintenance of this temperature may be the result of either a high rate of production and absorption of heat by the dust present at any given point or of a low rate of production and absorption. In other words, there might be vigorous combustion in the presence of considerable incombustible material or weak combustion in the presence of proportionately less incombustible material. With conditions nearly balanced, as they are when the limit of explosibility is approached, the rate of combustion initiated by the source of ignition could be continued over a zone of considerable length under fairly constant conditions of surroundings, and a relation between explosibility of the dust and igniting power of the source would be found. The results in figure 5 favor this hypothesis rather than that preceding.

APPLICATION TO TEST WORK

It is desirable to have as uniform dust-cloud conditions as possible when the effect of different factors, such as composition, on the explosibility of coal dust is being studied. Source *C* is the best of the three from the standpoint of formation of a dust cloud and consequently is preferable from the experimental standpoint. Its high igniting power will be of value when coals of low explosibility are studied, but it may fail to reveal differences between coals of high explosibility that would appear if a source with less igniting power is used. The gas-initiated propagation test in which source *C* is used has the disadvantage of being more expensive and time consuming than the standard propagation test using source *B*.

Mason and Wheeler [35] found that the dust-cloud density giving maximum explosibility varied considerably from coal to coal. Eleven British coals gave "optimum" concentrations ranging from 0.11 to 0.6 ounce under their test conditions. Until recently there was no evidence on the matter from Experimental mine tests beyond some scattered results with source *C* which indicated that the range of concentration for maximum explosibility was not likely to be large with that source. It may be expected to be larger with sources *B* and *A*. It is evident that this concentration will have to be determined with fair accuracy when source *C* is used. The flat top on the curve for source *B* (fig. 5) will make it possible to estimate a satisfactory concentration in many cases. It appears that source *A* is not suitable for comparing with precision the relative explosibilities of different coal dusts, and its usefulness is limited to the cases where there is direct application to commercial mines, as, for example, where there is a hazard of igniting freshly made coarse coal dust at a face or machine cuttings containing much high-ash impurity.

APPLICATION TO COMMERCIAL MINES

The percentage of incombustible material that should be maintained in the dust in commercial mines evidently depends on the maximum source of ignition that is likely to occur, as well as on the relative explosibility of the coal dust and other factors. This source cannot be predicted with accuracy in many instances, but results obtained in gas-initiated propagation tests are directly applicable to mines in which large amounts of methane are liberated. Gas explosions in such mines are not likely to be more severe than with source *C*, where gas is not permitted to accumulate as the result of neglected ventilation. Rock dusting cannot be made adequate to cope with the explosion of large bodies of gas whose accumulation is due to negligence in many instances.

If a mine is nongassy or only slightly gassy the most probable sources of ignition of coal dust are electric arcs and explosives. Standard propagation and ignition tests have direct application if black blasting powder is used in granular, pellet, or stick form, if

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[35] Mason, T. N., and Wheeler, R. V., work cited in footnote 33, p. 8.

blasting "off the solid" is practiced, or if permissible explosives are not permissibly used. In test work, the employment of pulverized Pittsburgh coal dust in the first 50 feet from the cannon can be considered equivalent to a longer zone of less explosive dust in some cases, and more exact information can be obtained by substituting dust from the particular mine for it, as has been done recently in several series of tests of coals from different beds.

If a nongassy mine uses permissible explosives the most probable cause of ignition of coal dust is an electric arc. A preformed dust cloud is required, and the necessary conditions have received only meager study to date, as noted below. Doubtless one could devise a source of ignition, using an electric arc and pure coal dust, which would give limits of explosibility comparable with those obtained in standard propagation tests. Considerable additional testing must be done before definite data are in hand.

Finally it must be kept in mind that under no conditions can the decrease in explosibility caused by the presence in mine passages of large quantities of coal dust per unit volume be relied on in determining the quantity of incombustible material that must be maintained in mine dust. The curves of figure 5 show that this decrease depends entirely on the conditions under which the explosion originates, and it is impossible to foretell these conditions in any mine. Rock dusting must be done with the idea of taking care of the worst conditions that are likely to occur.

It may be, however, that the information obtained in this investigation will assist in some instances in explaining the fact that explosions sometimes die out when they might be expected to continue.

MINIMUM GAS EXPLOSION REQUIRED TO IGNITE PURE COAL DUST

A question heard frequently among mining men is: "What is the smallest quantity of gas that, if ignited, will start a coal-dust explosion?" It is evident from the work discussed above that this quantity will depend chiefly on the power of the gas explosion to form and ignite a sufficiently dense coal-dust cloud. The quantity, distribution, size, and composition of the coal dust in the cloud present will also be contributing factors. The strength of the gas explosion will depend primarily on its volume, the percentage of gas present, the thoroughness with which the gas and air are mixed, and the point at which the mixture is ignited with reference to the confining walls.

As a guide to tests made in the Experimental mine in 1930 the above question was restated as follows: "What is the minimum volume of natural gas and air, uniformly mixed in proper proportions and ignited at the proper point to give maximum dust raising and igniting power, that will form and ignite a cloud of pulverized Pittsburgh coal dust placed in a manner most favorable to formation of a cloud in air?" Determinations made in accordance with these restrictions gave as nearly a true minimum as can be obtained under ordinary mining conditions. The minimum volume of gas found in these tests is smaller than is likely to cause an ignition of coal dust in a commercial mine because in such a mine conditions will usually be less favorable to an explosion occurring as regards distribution of dust and thoroughness of mixture of gas and air. Because of this the tests were extended to obtain further information on these points.

DUST ON MOVABLE SHELVES, UNIFORM GAS-AIR MIXTURE

Arrangements used in this group of tests are shown in figure 6. The gas-air mixture contained 9 to 10 percent gas in most tests and was confined by a paper diaphragm placed 6 feet from the face of the main entry. When a smaller volume was wanted the space was partly filled with sand. The mixture was ignited by an electric

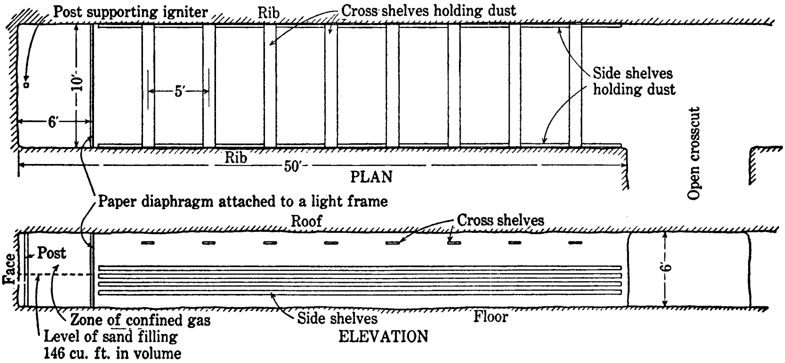

FIGURE 6.—Arrangement of gas zone and dust shelves in tests to determine minimum gas explosion required to ignite coal dust.

black powder igniter placed midway between roof and floor 6 inches from the face. Pulverized Pittsburgh coal dust was placed mainly on cross shelves so arranged that they would be upset by the gas explosion. In some tests one third of the dust was on fixed longitudinal side shelves. The results of the tests are given in table 3.

TABLE 3.—*Tests to determine minimum quantity of uniform natural gas-air mixture required to raise pulverized Pittsburgh coal dust and initiate a self-sustained explosion under most favorable conditions*

Test no.	Volume of gas zone [1]	Quantity of coal dust		Maximum pressures		Length of flame			Could initial dust explosion become self-sustained?
		On movable cross shelves	On fixed side shelves	E1258	E1150	Greatest extension	Beyond coal dust		
							Entry	Crosscut	
	Cu. ft.	*Pounds*	*Pounds*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Feet*	*Feet*	*Feet*	
1154	304	None.	None.			33			
1155	304	25	None.			43	12		No.
1156	304	[2] 50	None.	0.2	0	43	0		No.
1157	304	50	25	1.3	2.7	83	8	33	Yes.
1158	304	33	17	1.0	3.0	58	8	0	No.
1159	304	50	25	1.0	3.0	90	33	33	Yes.
1160	223	50	25	1.5	4.0	90	33	33	Yes.
1161	146	50	25	1.2	3.3	90	33	33	Yes.
1163	101	None.	None.	.3	1.0	13			
1164	101	None.	None.			8			
1165	101	50	25			8	0	0	No.
1166	101	50	25			13	0	0	No.
1167	[3] 146	50	25			18	0	0	No.
1168	[3] 146	50	25	.3	.9	38	8	0	No.

[1] There was 9 to 10 percent gas in the mixture except in the following tests: 1159, 7.4 percent; 1163, 12.8 percent; 1166, 8.6 percent; 1167, 8.7 percent.
[2] In this test only first 5 shelves were movable; others were fixed.
[3] See text for alteration in arrangement of gas zone in this test.

Volume of gas mixture, 304 cubic feet.—This volume was used in 6 tests. Flame extended 33 feet from the face in the absence of dust in test 1154. Addition of 25 pounds of coal dust on 5 movable cross shelves extended the flame 10 feet in test 1155, but the ignition was evidently poor. Further addition of 25 pounds of coal dust on 5 fixed cross shelves immediately outby the movable ones gave no additional length of flame in test 1156. In test 1157 there were 50 pounds of coal dust on 10 movable shelves and 25 pounds on fixed side shelves; a strong ignition was obtained which would have developed into a self-sustained explosion had the necessary dust been present. The relative distribution of dust used in test 1157 was retained in test 1158, but the total quantity was reduced to 50 pounds, and a poor ignition was obtained. Test 1159 duplicated 1157, and strong ignition was obtained again. It was evident that the quantity and arrangement of coal dust used in tests 1157 and 1159 were satisfactory, and they were kept unchanged in all following tests in which dust was used.

Volume of gas mixture, 223 and 146 cubic feet.—The above tests indicated that the volume of gas-air mixture used might be reduced. Volumes of 223 and 146 cubic feet were used in tests 1160 and 1161, respectively, and strong ignitions were obtained in both cases. There was no doubt that self-sustained coal-dust explosions would have developed had the necessary dust been present beyond the portion of the test zone used.

Volume of gas mixture, 101 cubic feet.—This volume was used with no dust present in tests 1163 and 1164. The former test is disregarded because the percentage of gas was too high. In the latter flame did not extend much beyond the confines of the gas mixture itself. Coal dust placed outby this volume was not ignited in tests 1165 and 1166. The pressure developed by the gas explosion was insufficient to overturn the movable shelves.

Effect of additional release of pressure.—Test 1161 showed that 146 cubic feet of a 9-percent gas-air mixture could cause ignition of the coal dust under the conditions used. In this test the burning gas could expand outward only, and it was possible that expansion in a second direction would have an adverse effect on ignition. The sand filling was removed and a paper diaphragm substituted for its upper surface in tests 1167 and 1168. Rupture of this diaphragm permitted expansion downward as well as outward. The dust was not ignited in test 1167, and the ignition in test 1168 was very feeble. The additional release caused a decrease in the dust-raising power of the gas explosion.

The volume of gas-air mixture whose explosion is required to ignite fine bituminous coal dust is small, so small that it is liable to be considered a negligible hazard by many mining men. As the gas was 9 percent of the mixture, only 13 cubic feet were present in test 1161. This quantity of gas can be confined at atmospheric pressure in a cubical box 2 feet 4½ inches on a side. The mixture itself would occupy little space in a mine entry. If a 12-foot entry is driven to the rise on a grade of 1 in 10, a mixture 19 inches deep at the face and tailing out on a level line has a volume of 150 cubic feet.

In the above tests the dust was placed in positions most favorable to formation of a cloud thereof by a disturbance in the air, and equally favorable conditions for starting an explosion will not be met frequently in mines unless there is some secondary dust-raising power such as might come from a fall of roof. The following tests were made to determine the minimum amount of gas-air mixture required when a dust cloud is formed less readily.

DUST ON FIXED SHELVES, UNIFORM GAS-AIR MIXTURE

In tests 1194 and 1195, 300 cubic feet of gas mixture were confined and ignited at the face as shown in figure 6. One hundred and fifty pounds of pulverized Pittsburgh coal dust were distributed on fixed cross and side shelves to E1200 and A1250. In test 1194 the first cross shelf was about 50 feet from the face. Flame traveled through the coal dust but was extinguished immediately outby by mixed dust containing about 60 percent incombustible material. In test 1195 additional cross shelves were placed nearer the face, but results were unchanged.

The volume of gas-air mixture was increased to 500 cubic feet in tests 1196 and 1197 by placing the diaphragm 10 feet from the face. Pulverized coal dust was distributed to E1150 and A1200 in test 1196, with equal division between cross shelves, side shelves, and floor. Outby this was a mixture containing 60 percent incombustible. A strong explosion resulted, and flame extended 600 and 800 feet beyond the ends of the pure coal-dust zone in the entry and air course, respectively.

Test 1197, on April 23, 1930, was a demonstration for the chief mine inspectors of Pennsylvania, West Virginia, Ohio, and Illinois. The gas and pure coal-dust zones were the same as in 1196. Outby the pure coal dust there was placed to E950 and A950 a mixture containing approximately 54 percent incombustible material. A strong explosion extending throughout the main entry was obtained; and flame was projected from the entry portal. In the air course it died out about 350 feet from the portal, probably because of release of pressure from behind the flame in nos. 1 and 2 left butt entries.

Tests 1194 and 1195 showed that explosion of 300 cubic feet of a 9 percent gas-air mixture was sufficient to ignite pure coal dust on fixed shelves simulating mine timbers, but the explosion did not gain enough strength in a distance of 200 feet to proceed through dust containing considerable incombustible material. Nevertheless, it might have developed strongly had there been a zone of pure coal dust 2 or 3 times as long. Increasing the volume of gas mixture to 500 cubic feet in tests 1196 and 1197 resulted in an explosion which traveled long distances through a mixture which contained 60 percent incombustible and was apparently capable of traveling indefinitely in a mixture containing 54 percent. The volume of gas required to initiate an explosion in pure fine coal dust was 2 to 3 times as great when the dust was on fixed shelves as when on shelves that could be overturned but was still not a large body—only 10 feet long—when judged from the standpoint of the average mining man.

The gas conditions in these tests were as severe as can be obtained in a similar volume of gas in a commercial mine, as the gas and air were thoroughly mixed. The following tests were made to obtain information on what may be expected when the gas is stratified or in a layer close to the roof.

DUST ON MOVABLE SHELVES, BODY OF GAS AT ROOF

Tests 1169 to 1180 were made to study explosions of strata of gas close to the roof. Such conditions are found where gas issues from the roof faster than it can diffuse in the quiet air of a heading in advance of ventilation. All tests were conducted in the dead end of the main entry, and the pulverized Pittsburgh coal dust, when used, was on movable cross shelves as shown in figure 6. Natural gas was admitted at low velocity from a 3-inch-diameter pipe placed close to the roof at the face; this minimized the effect of turbulence caused by the movement of the gas. Ignition was by a black powder igniter so arranged that burning powder grains were projected upward into the gas from a point about 2 feet above the floor and close to the face unless otherwise noted.

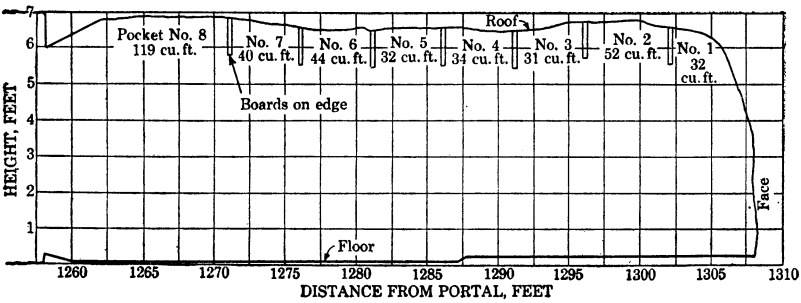

FIGURE 7.—Arrangement of pockets in roof for holding gas in tests 1171 to 1180.

Gas explosions with no dust present.—There was no dust on the shelves in the first five tests. In nos. 1169 and 1170 a paper diaphragm 10 feet from the face held all the gas in the space so enclosed. In test 1169 the explosion of 25 cubic feet of gas tore loose and charred the diaphragm and projected flame 7 feet beyond it, but there was insufficient force to upset any empty shelves. The explosion of 50 cubic feet of gas in test 1170 projected flame 27 feet beyond the diaphragm, but again no shelves were upset.

The method of confining the gas was then changed to that shown in figure 7, a system designed to simulate the effect of timber sets at 5-foot intervals along a heading. Boards placed on edge were fitted to the roof to form pockets, after which they were plastered so that gas could pass from one pocket to another only by flowing under them. Gas was admitted in pocket 1 (see fig. 7) and allowed to spread freely; ignition was in this pocket unless otherwise noted. Twenty cubic feet of gas gave 28 feet of flame in test 1171, and 50 cubic feet gave a maximum of 38 feet of flame in tests 1172 and 1173. None of the empty shelves were upset in these tests.

Gas explosions with coal dust present.—Coal dust was placed on the shelves beginning with test 1174, in which 50 cubic feet of gas gave 38 feet of flame and shelves 5 and 7 (numbered from the inner end) were upset without ignition of the dust following. Seventy-five cubic feet of gas gave 33 feet of flame in tests 1175 and 1176 without producing enough force to upset a shelf. A paper diaphragm was then placed at the outer end of pocket 8 to prevent a suspected escape of gas therefrom. Use of 80 cubic feet of gas in tests 1177 and 1178 gave results no different from those obtained in 1175 and 1176. The quantity of gas was increased to 170 cubic feet in test 1179, and 58 feet of flame resulted, but again no shelves were upset. Test 1180 duplicated 1179, except that ignition was at pocket 7; results were the same as in 1179. Approximately 10 minutes elapsed between admission of the last of the gas and ignition thereof in all these tests.

Distribution of gas.—Interspersed with these tests were several determinations of the percentage of gas in the pockets. The desired quantity was admitted, and samples were taken immediately at the highest point in each pocket by the vacuum-bottle method. The pockets were then ventilated and a fresh quantity of gas admitted before an explosion test was made. The analyses of three sets of samples follow:

Gas in pockets, percent

Set no.	Gas admitted, cubic feet	Pocket no.							
		1	2	3	4	5	6	7	8
1	75	75.2	34.2	14.6	7.5	3.7	0.8	0.5	0.2
2	75	90.9	56.0	28.2	.2	8.1	3.2	.9	1.4
3	170	93.8	72.4	54.0	42.4	32.1	10.5	15.4	3.3

Seventy-five cubic feet of gas filled the first 4 or 5 pockets to or above the explosive range. The sample from pocket 4 in the second set is probably in error for some unknown reason. Use of 170 cubic feet filled all the pockets similarly except the last.

Additional samples were taken to show the variation in quantity of gas present at different distances from the roof in and under pocket 2. The results follow:

Variation in quantity of gas vertically, percent

Distance from roof, inches	Gas in samples of set—			Distance from roof, inches	Gas in samples of set—		
	1	2	3		1	2	3
2	73.8		70.6	18	10.0	1.2	0.9
6	72.5		73.2	22		.4	.4
10	72.2		54.7	26		.2	.4
14 [1]	59.2		6.5	30		.1	.4

[1] This point level with lower edge of boards forming the pocket.

The first set showed an explosive mixture 4 inches below the bottom of the pocket, and the second set was taken to see how much farther downward it extended. The results did not agree, and the third set was taken. Evidently the flow of gas was erratic, as most of the air was displaced from the pocket, but at and below the lower edge thereof there were wide variations.

Summary.—Shelves were upset in only one test with stratified gas, and then the dust was not ignited. The maximum quantity of gas used was 13 times that needed in a uniform mixture with air to initiate an explosion in the same dust similarly placed. The results of tests so far made are entirely inconclusive and show the need of thorough investigation of the spread of gas issuing as from a drill hole, a machine overcut or shear, or a roof slip, and its mixture with air as promoted by diffusion, convection, and eddy currents caused by movements of men or machinery. This information is needed as a foundation for a study of the igniting and dust-raising powers of explosions of nonuniform mixtures of gas and air under conditions akin to those liable to be found in commercial mines.

ELECTRIC ARCS AS SOURCES OF IGNITION OF COAL DUST

Many disastrous coal-dust explosions in mines in the United States have started from direct ignition of a cloud of coal dust by an electric arc in fresh intake air. In some of these instances the dust cloud

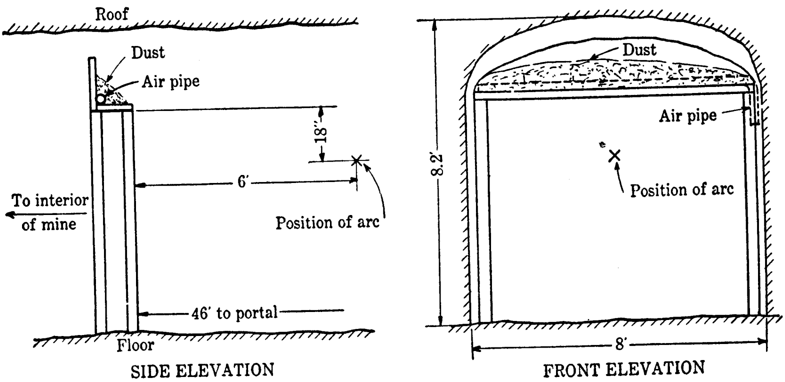

FIGURE 8.—Arrangement of first device for demonstrating ignition of coal dust by an electric arc.

was produced by wreckage of a trip of cars which, in turn, threw down timbers; in others there was derangement of some other coal-carrying device. The arc came from a trolley wire or power cable that was cut or short-circuited by contact with a steel pit-car body or car irons. Hundreds of lives have been lost in these disasters. Their frequency is increasing, yet some mining men were skeptical of the possibility of such a thing happening, especially in fresh intake air, and this led to the development in 1925 of a device by which such an ignition could be demonstrated.

FIRST DEMONSTRATION DEVICE

These demonstrations were carried out in the entry pit mouth, and the method used is illustrated in figure 8. The air pipe in the corner of the shelf was 1 inch in size, and 1/4-inch holes were bored in it at 6-inch intervals. Admission of compressed air to the pipe blew a cloud of pulverized Pittsburgh coal dust onto the arc formed by an arc lamp of the type formerly used for street lighting. The protecting glasses were removed, and the dust cloud came in direct contact with the arc, which carried 6.5 amperes with a potential drop of 65 volts across the carbons.

Ignition of the dust could be observed either from outside the mine or from a point 50 or more feet to the rear of the shelf. In the latter case, safety of the observers was assured by rock dust in the entry and by having a strong current of air moving past the shelf holding the coal dust and out the entry portal, as the ignition was too close thereto to allow the burning dust cloud to travel inward. A spectator saw the arc obscured momentarily by the dust cloud; then flame started from it and spread through the cloud rapidly, rushing to the portal and expanding in the open air. Failures of ignition were exceptional when high-volatile coal dust was used and could be traced to improper functioning of the apparatus. A few trials of a low-volatile bituminous coal indicated that this particular arc was not sufficient to cause ignition thereof. Of course,

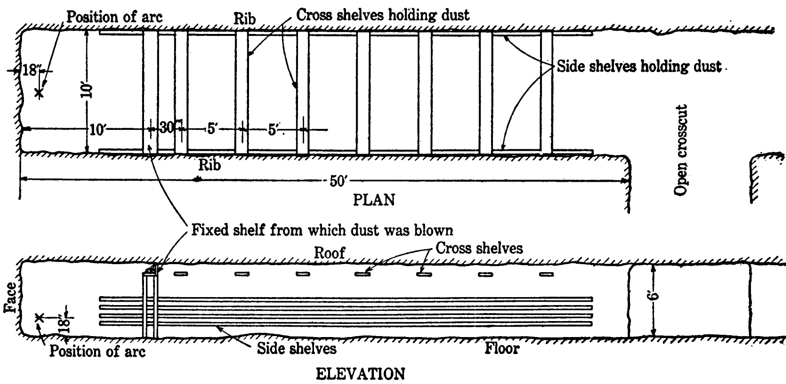

FIGURE 9.—Arrangement of arc lamp and dust shelves at face of main entry.

this arc is small compared with those in commercial mines where the current drawn in a direct short circuit may be hundreds of amperes at 250 to 500 volts. Such arcs have enormously greater igniting power.

TESTS AT FACE OF MAIN ENTRY

The above device was used at the face of the main entry in March 1930 to determine the minimum amount of pulverized Pittsburgh coal dust that had to be blown onto the arc to produce an inflammation that would raise dust from surrounding surfaces and initiate a self-sustained explosion. The arrangements are shown in figure 9; they differed from those of figure 8 only in that the arc was nearer the floor and a little farther from the shelf. A solenoid-controlled valve was placed in the air line and operated from outside the mine. Outby the shelf carrying the air pipe were cross shelves balanced on narrow supports so that a small force would upset them and form a dust cloud. These were in addition to the regular fixed side shelves. The tests may be divided into those in which (1) there was dust only on the fixed shelf carrying the air pipe and (2) additional dust was placed on movable or fixed shelves outby.

Dust on fixed shelf only.—The primary data of seven tests in this group are given in table 4.

TABLE 4.—*Results of tests in which varying quantities of coal dust were blown onto an electric arc*

Test no.	Quantity of dust	Length of flame	Pressure, pounds per square inch		Time taken for flame to travel 50 feet
			50 feet from arc	150 feet from arc	
	Pounds	*Feet*			*Seconds*
1181	100	75	2.5	6.0	0.42
1182	50	75	1.3	5.5	.32
1183	25	50	----------	6.3	.17
1184	10	50	----------	----------	
1185	10	35	.5	1.5	----------
1186	10	50	.8	2.4	1.05
1187	5	20	.1	.5	----------

A strong ignition was obtained with 100 pounds of coal dust, and reduction to 50 pounds caused no decrease in the length of flame, slight decrease in pressure, and increase in the velocity of flame travel. Further reduction to 25 pounds shortened the flame about one third, but the pressure was closely the same as with 100 pounds of dust, and the flame velocity was increased again. The instruments failed to operate in the first test with 10 pounds of dust (no. 1184), and the two following tests were duplicates thereof. Pressure was reduced considerably, and flame length varied somewhat; in test 1185 the foil 50 feet from the arc was not fused. The velocity in test 1186 was much lower than in any of the preceding tests.

A good inflammation was obtained in test 1187 with only 5 pounds of dust, but ignition was not obtained in two subsequent trials. Evidently a dense enough part of the dust cloud did not come in contact with the arc.

It will be noted that the pressure 150 feet from the arc and 50 to 100 feet beyond the end of the flame was greater than at a point 50 feet from the arc and in the flame of some of the tests. The burning coal dust sent out a continuous series of pressure waves, and under the conditions of these tests the later ones traveled faster and overtook those that preceded. There resulted a single wave of higher pressure and steeper front. In a commercial mine such a wave might blow out doors or break down stoppings at points considerably in advance of the end of the flame, provided that its pressure was not relieved by expansion into side entries or other open spaces.

Additional dust on movable or fixed shelves outby.—Tests 1188 to 1190 were made to determine if a self-sustained explosion could develop from an inflammation of 10 pounds of coal dust such as occurred in tests 1184 to 1186. In test 1188, 50 pounds of coal dust were placed on the movable shelves, and flame extended about 35 feet beyond the last shelf; pressures were twice as great as in test 1186. In test 1189 an equal amount of dust was on the fixed side shelves and the floor only, a condition more similar to that found in a commercial mine. Flame traveled through the dust loading but did not extend much beyond. The conditions of test 1189 were repeated in 1190, with the addition of 50 pounds of coal dust in the open crosscut. Flame extended at least 100 feet beyond the ends of the dust loading, and pressures of 5 to 9 pounds were recorded. This was ample proof that the inflammation of 10 pounds of fine Pittsburgh coal dust by a small electric arc could develop into a self-sustained explosion under suitable conditions.

These tests show the great importance of using safeguards at the working faces where electrically driven machines used for mining, loading, and other purposes produce large quantities of coal dust during their operation. The test results point to the necessity of using water to allay dust at such places and of using only permissible electric machinery. Emphasis is placed on the need of thorough rock dusting on haulageways where a derailed trip may produce a dense cloud of coal dust and a simultaneous arc through short-circuiting of a trolley wire or power cable. The foregoing tests need to be supplemented by others giving information on the relative danger of arcs of different voltage and amperage, the effect of altering the distribution of the dust, and the relative ease of ignition of different coal dusts.

SECOND DEMONSTRATION DEVICE

Conditions surrounding trolley haulage in operating mines were simulated more closely by a second demonstration device developed after the above tests were made. Figure 10 is a photograph of the final form thereof. The arc appears as a white spot at the right end of the car and is formed between the roller bar and a piece of trolley wire. The vertical rod supporting the wire near the arc is attached to the plunger of a solenoid electromagnet, which is included in a circuit with the wire and gate bar. Closing the circuit raises the wire and forms the arc; if the arc breaks, the wire falls and contact is remade. The circuit is connected to a 250-volt supply, and the current can be varied between 20 and 100 amperes.

In the first trials the coal dust was blown from a shelf, as shown in figure 8. The arrangement of a trough across the end of the car as shown in figure 10 was adopted later; in one form the trough can be rotated about its horizontal axis so that the dust cloud is blown in any desired direction. There is a perforated pipe at the bottom of the trough, and admission of air to form the dust cloud is controlled by a valve operated by a solenoid. The device can be operated in the open if protected from disturbance by wind, and figure 11 is a photograph of an ignition of Pittsburgh coal dust so obtained.

DEMONSTRATION EXPLOSIONS

This device was used a number of times to initiate explosions made as demonstrations for groups of mining men and others. The first of these were tests 1208 to 1212, made in September and October 1930, of which tests 1208 to 1210 were preliminary, to determine the most suitable conditions. Location of the car at E160 did not give satisfactory results; this point is too near the portal. The car was then placed at E325, and 1,000 pounds of coal dust were distributed on temporary shelves extending from E500 to the portal.

FIGURE 10.—Second device for demonstrating ignition of coal dust by an electric arc.

FIGURE 11. —Ignition of a coal-dust cloud in open air by an electric arc.

This arrangement gave an explosion in test 1209 that had a short sharp flame outside the mine, accompanied by a concussion that broke windows a half mile away. The coal-dust arrangements of test 1209 were retained in 1210, but the car was located at E275. Flame extended 200 feet out of the portal and about 150 feet vertically. The accompanying concussion broke windows at several points on the grounds.

The arrangements of test 1210 were repeated in 1211 made on October 1, 1930, as a demonstration for members of the National Safety Council then in session at Pittsburgh. About 300 visitors were present. Flame extended 200 feet from the portal, and fragments of the temporary shelves were thrown equally far. An empty mine car standing in front of the portal was hurled 75 feet into the reservoir, and a number of surrounding buildings were damaged by violence. In the mine flame extended inby 250 feet beyond the end of the coal-dust zone and pressures up to 45 pounds were recorded.

Test 1212 was made on October 25, 1930, before a group of 108 mining men from Westmoreland County, Pa. Arrangements of test 1211 were duplicated except that the dust from E325 to E500 was made coarser and contained 40 percent incombustible material to reduce violence. The resulting explosion projected an even larger volume of flame from the portal but without concussion and was, on the whole, less spectacular. Maximum pressure in the mine was 10 pounds per square inch.

There have been three additional demonstrations of this nature, tests 1264 and 1265 on November 28 and December 2, 1931, and 1280 on February 6, 1932. The first and last were for members of classes taking the accident-prevention courses given by the Safety Division of the Bureau. The second was for the purpose of obtaining sound pictures for educational purposes which appeared throughout the United States in Paramount Sound News during the week ended December 24, 1931.

IGNITION OF LOW-VOLATILE COAL DUSTS

A larger arc is required to ignite low-volatile than high-volatile coal dusts. To date experiments with low-volatile coal dusts have been confined to trials of pulverized dust with the 100-ampere arc of the second demonstration device. The following coals have been used.

Low-volatile coals tested

Designation	*Ratio of volatile to total combustible*
Pocahontas no. 5 bed, McDowell Co., W.Va., first mine	0.253
Pocahontas no. 5 bed, McDowell Co., W.Va., second mine	.232
Pocahontas no. 3 bed, Tazewell Co., Va	.243
Pocahontas no. 3 bed, McDowell Co., W.Va	.242
Lower Kittanning bed, central Pa	.187
Pocahontas no. 4 bed, McDowell Co., W.Va	.163

Ignition was obtained readily with the first 4, but not with the last 2 dusts. The tests of lower Kittanning dust were made before the second demonstration device was fully developed and are not considered to be conclusive. The Pocahontas no. 4 bed coal was used under a number of different conditions and the best ignition obtained gave a ball of flame about 2 feet in diameter, but the flame did not spread through the remainder of the dust cloud. It did do so, however, when there was 1.6 percent natural gas in the air current.

The foregoing results are too fragmentary to permit drawing conclusions. Under a standard method of test one may expect to find some relation between volatile ratio of a coal and minimum arc required for its ignition. A 100-ampere arc dissipating 20 to 25 kw of power may be expected to ignite pulverized dust of any coal whose ratio of volatile to total combustible material is 0.24 or higher. The size of arc required will certainly decrease as the volatile content increases.[36]

MISCELLANEOUS SOURCES OF IGNITION OF COAL DUST

A number of different sources of ignition were used during an investigation of barriers to test their sensitivity or to produce explosions having certain desired characteristics.

GAS EXPLOSIONS AS SOURCES OF IGNITION

The gas explosions differed from those used as source *C* in one of two ways: (1) The full-size body of gas was ignited at some point near its outer end, or (2) the size was reduced one half.

IGNITION OF A 50-FOOT BODY AT DIFFERENT POINTS

Tests 770 to 781, made in the fall of 1925, were of gas-air mixtures prepared in the manner prescribed for source *C;* no dust was present. The point of ignition was 8 to 13 feet from the diaphragm, and the only instrument records obtained were length of flame and pressure at E950. In all tests flame length was the same as given by source *C*, but pressure decreased from 3.8 to 1.4 pounds as the point of ignition was moved closer to the diaphragm, compared with 9 pounds given by source *C* at this point. Moving the point of ignition toward the diaphragm confining the gas caused a large decrease in dust-raising power, but the extent of the flame suggests that any decrease in coal-dust igniting power was proportionately much smaller.

Similar results were obtained in tests 1022 and 1024, made in March 1928, with ignition 12 feet from the diaphragm. The ability of such gas explosions to initiate coal-dust explosions was investigated in tests 1020 and 1021 in which mixtures of mine-size Pittsburgh coal dust were placed in the standard test zone extending to E950 and A950. Explosions were obtained in both instances, showing that the decrease in dust-raising power caused by moving the point of ignition was not sufficient to prevent formation of a proper dust cloud.

USE OF SHORTER BODIES OF GAS

In tests 1025 and 1026 the body of gas-air mixture was 25 feet long. Ignition was 12 feet from the face in test 1125, and flame

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[36] "A short-circuited lighting line is believed to have been responsible for the explosion in the Kinloch mine, Westmoreland County, Pa., on Mar. 21, 1929, whereby 46 lives were lost * * * the bin or loading compartment was lighted by 50- and possibly 100-watt lamps on a 250-volt circuit * * *.

"A conveyor under full load broke * * * and very rapidly descended into the slope." (The main intake) * * * "The sudden impact of the conveyor at the foot of the slope * * * threw into suspension a dense cloud of coal dust." Annual Rept. for 1929–30, Pennsylvania Department of Mines, pt. 2, pp. 14–19.

extended to E1200 and A1250; pressure at E950 was 2.6 pounds. Ignition was 19 feet from the face in test 1026, and flame extension was practically the same as in 1025, but the pressure at E950 was reduced one half. It is noticeable that reducing the volume of gas mixture one half did not have a proportionate effect on flame length and pressure. This probably would not be the case in a single heading.

BLOW-OUT SHOTS AS SOURCES OF IGNITION

During the investigation of barriers there were a number of trials of blow-out shots of black blasting powder in which the quantity of powder was reduced below the standard 4 pounds. The cannon was at the face of the main entry in all cases. A shot of 2 pounds of powder stemmed with 1 pound of clay did not produce enough concussion to raise pulverized Pittsburgh coal dust from the floor 12 inches below the borehole in sufficient quantity to give an ignition. A bench 2 feet wide by 10 feet long was then placed in front of the cannon with its top surface less than one half inch below the level of the bore. One pound of powder stemmed with 1 pound of clay caused ignition of pulverized Pittsburgh coal dust placed on the bench. Use of 1.5 pounds of powder in the cannon with pulverized coal dust on the bench and from the cannon to E1240 developed an explosion which traveled to E950 and A950 through a dust mixture containing 50 percent incombustible material. It was possible to obtain explosions of any desired speed and violence by increasing the quantity of powder in the cannon and the length of the pure coal-dust zone. A powder charge of 2.5 pounds, together with 120 pounds of coal dust distributed from the cannon to E1225 and A1250, resulted in explosions which reached E950 and A950 in less than 1 second and produced pressures of 20 to 30 pounds per square inch at those points. The mixed dust outby the pure coal dust contained 50 percent incombustible in these tests.

GELATIN DYNAMITE AS A SOURCE OF IGNITION

Mud-capped shots of gelatin dynamite have caused explosions in coal mines in several instances, and a method of demonstrating this has been developed. A stick or portion of a stick of 40 percent gelatin dynamite is buried loosely in a pile of about 35 pounds of coal dust and detonated. This throws the coal dust into the air and ignites it. The demonstration can be made either in the open or in the air course pit mouth; in the latter case additional dust is placed on temporary cross shelves in the vicinity of the shot, and an explosion of all the dust results. Flame is projected from the portal with considerable force as well as from the small air shaft that is connected to the air course near the portal.

A half stick of dynamite is sufficient for high-volatile coals, but a full stick is needed for low-volatile ones. Coals from the Beckley and Pocahontas Nos. 3, 4, and 5 beds, West Virginia, have been tested, and ignitions were obtained in all cases.

All shots of explosives in coal mines should be in drilled holes properly stemmed and the explosive should always be permissible explosive.

EFFECT OF DISTRIBUTION OF DUST ON PROPAGATION

Dusts at different points on the perimeter of a mine passageway differ considerably in size and in composition, particularly in rock-dusted mines. The higher a given dust is above the floor, the more easily is a cloud formed by a given concussion, and all these factors operate to give different explosibilities to dusts in different locations. A study of the effect of altering the distribution of dust from that used in standard tests was made in 1925 and 1926, but it became evident that an extensive investigation was required and it was not possible to carry the work to a conclusion at that time, or to resume it since. It is possible to draw only a few qualitative conclusions from these tests.

ALTERATION OF DISTRIBUTION OF A GIVEN DUST MIXTURE

Seven tests were made of a mixture containing 40 percent of mine-size Pittsburgh coal dust and 60 percent of shale of which 30 percent was minus 200-mesh. Initiation was by source *B*, and the mixture was placed to E950 and A950 at the rate of 1 pound of coal dust per linear foot, which is equivalent to 0.267 ounce per cubic foot. In different tests the mixture was used on the floor, side shelves, and cross shelves separately, equally divided between all possible combinations of 2 of the 3 positions, and equally divided between all 3. Results of the tests are given in table 5.

TABLE 5.—*Tests of different distributions of a mixture of 40 percent mine-size Pittsburgh coal dust and 60 percent shale, of which about 30 percent was minus 200-mesh; initiation by source B*

Test no.	Proportion of mixture on—			Maximum pressure at—		Length of flame measured from cannon		Results [1]
	Cross shelves	Side shelves	Floor	E950	A950	Entry	Air course	
	Percent	*Percent*	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Feet*	*Feet*	
676	100	0	0	1	1	150	300	NP.
677	0	100	0	1	1	150	250	NP.
675	0	0	100	1	1	125	125	NP.
686	50	50	0			350	400	P.
685	50	0	50			300	400	PP.
687	0	50	50			150	250	NP.
678	33⅓	33⅓	33⅓	2	3	350	400	P.

[1] Abbreviations used: P., propagation; PP., partial propagation; and NP., nonpropagation.

Propagation was not obtained with dust in any one position alone, but use of the cross shelves gave greatest flame extension. Dividing the dust between two positions gave complete propagation only when cross and side shelves were used. Propagation was obtained when the dust was in three positions, as in standard tests. Variations in the results are to be connected with changes in the dust cloud formed. Use of cross shelves was most favorable and of the floor least favorable to dust cloud formation. The standard method of distribution is, apparently, as good as can be obtained for production of a uniform dust cloud without major alteration of the test zone, such as doubling the number of cross shelves. This would place them 5 feet apart, as is often the case with cross timbers for support of roof. Different results may be expected with such an arrangement.

LIMITS OF EXPLOSIBILITY OF COAL-DUST MIXTURES IN DIFFERENT POSITIONS

It was next decided that the limit of explosibility of mine-size Pittsburgh coal dust should be determined with all seven distributions shown in table 5. The inert dust was to contain 70 percent of minus 200-mesh material to correspond more closely with that in use in commercial mines. It was necessary to vary the rate of coal dust loading in these tests as nothing was known concerning the minimum allowable under such conditions. The series of tests was incomplete, but such results as were obtained are given in table 6.

TABLE 6.—*Tests of different distributions of mixtures of mine-size Pittsburgh coal dust and shale dust of which 70 percent was minus 200-mesh; initiation by source B*

Test no.	Incombustible content of mixture	Quantity of coal dust	Maximum pressures		Length of flame measured from cannon		Results[1]
			E950	A950	Entry	Air course	
	Percent	*Oz. per cu. ft.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Feet*	*Feet*	
1. LOADING ON CROSS SHELVES ONLY							
845	54	0.127	1	1	225	325	NP.
2. LOADING ON SIDE SHELVES ONLY							
844	45	0.152	2	2	350	400	P.
836	49	.140	1	1	175	275	NP.
835	59	.127	1	1	150	250	NP.
3. LOADING ON FLOOR ONLY							
846	40	0.158	1	1	150	275	NP.
830	40	.307	3	2	350	400	P.
847	45	.128	1	1	125	225	NP.
829	45	.248	2	2	150	250	NP.
849	45	.373	1	1	225	350	NP.
850	45	.498	1	1	200	150	NP.
827	54	.165	1	1	150	225	NP.
4. LOADING EQUALLY DIVIDED BETWEEN CROSS AND SIDE SHELVES							
832	59	0.228	6	5	350	400	P.
833	63	.203	1	3	350	400	P.
834	68	.178	1	2	150	275	NP.

[1] Abbreviations used: P., propagation; and NP., nonpropagation.

A satisfactory limit of explosibility was obtained only with dust on the floor alone because of insufficient data. A limit of 43 percent incombustible is indicated, compared with 57 percent for the same dust loaded in the standard manner. The difference between these figures may be taken as a rough measure of the additional difficulty of forming a cloud when the dust is on the floor only. The incomplete results obtained with dust on cross and side shelves (part 4 of the table) indicate a limit of about 65 percent incombustible. Whatever the final conclusion, there is definite evidence that dust on the floor may safely contain somewhat less incombustible material than that on ribs and cross timbers under conditions similar to those of the tests, but additional experiments must be made to determine the difference exactly.

DIFFERENT MIXTURES OF DUST ON SHELVES AND FLOOR

The above group of tests was extended to include use of different dust mixtures on shelves and floor with loading to E950 and A950, as in the above tests. Such tests as were made are summarized in table 7.

TABLE 7.—*Tests in which the dust mixture on side and cross shelves differed from that on the floor; mixtures of mine-size Pittsburgh coal dust and shale dust containing 70 percent of minus 200-mesh material; initiation by source B*

Test no.	Incombustible content of mixture			Quantity of coal dust			Maximum pressure		Length of flame measured from cannon		Results[1]
	On shelves	On floor	Weighted average	On shelves	On floor	Total	E950	A950	Entry	Air course	
	Percent	*Percent*	*Percent*	*Oz. per cu. ft.*	*Oz. per cu. ft.*	*Oz. per cu. ft.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Feet*	*Feet*	
1. DUST ON CROSS SHELVES AND FLOOR ONLY											
842	68	45	54	0.089	0.248	0.337	1	1	250	325	NP.
2. DUST ON SIDE SHELVES AND FLOOR ONLY											
841	59	45	50	0.114	0.248	0.362	3	3	350	400	P.
843	63	45	52	.101	.248	.349	2	2	350	400	P.
838	68	45	54	.089	.248	.337	1	1	200	325	NP.
837	82	45	59	.051	.248	.299	1	1	175	300	NP.
839	82	40	56	.051	.269	.320	2	1	225	400	PP.
3. DUST ON CROSS SHELVES, SIDE SHELVES, AND FLOOR											
823	68	45	61	0.178	.0123	0.301	2	2	350	400	P.
820	68	45	58	.178	.248	.426	4	2	350	400	P.
819	68	49	60	.178	.203	.381	2	2	250	300	NP.
818	68	59	65	.178	.136	.314	1	1	125	225	NP.
826	82	36	66	.101	.191	.292	2	2	250	400	PP.
831	82	40	60	.056	.153	.209	1	1	175	300	NP.
825	82	40	69	.101	.153	.264	2	2	200	325	NP.
828	82	40	62	.101	.307	.408	3	2	350	400	P.
824	82	45	71	.101	.123	.224	1	1	150	225	NP.
840	82	45	65	.101	.248	.349	1	1	100	175	NP.
848	100	40	71	.000	.307	.307	1	1	50	100	NP.

[1] Abbreviations used are: P., propagation; PP., partial propagation; and NP., nonpropagation.

Dust on side shelves and floor only.—These tests were designed to represent conditions in an untimbered entry with smooth roof on which little dust collects compared with that found on ledges of the ribs. Tests 838 and 837 show that it was possible to prevent propagation of flame by having a high percentage of incombustible on the side shelves when that on the floor was low. At least part of this effect is to be ascribed to poor dust-cloud formation, as the following considerations show. The weighted average incombustible content of all the dust was 54 percent in test 838 and 59 percent in test 837. Uniform mixtures of these compositions would be strongly explosive if subjected to the gas-initiated propagation-test method, the quantity of coal dust present remaining unchanged. The former would be explosive and the latter close to the limit under standard propagation-test conditions.

The tests give additional evidence that the incombustible content of the dust on the floor can be lower than that of dust on the ribs, but the allowable difference and the minimum allowable incombustible content of the floor dust will depend on the dust-raising power of the source of ignition as well as on the relative positions of the dusts.

Dust on cross shelves, side shelves, and floor.—In these tests a given dust mixture was used on the side and cross shelves and another of lower incombustible content was placed on the floor. There are four variables in the case—the quantity and composition of the dust in each location—and the data are not complete enough to permit proper evaluation of them. Qualitatively the results are the same as obtained with dust on the side shelves and floor only; the incombustible content of the floor dust can be lower, but there is a minimum below which it cannot be allowed to pass. Again one should expect different results if a more powerful source of ignition was used. It is probable that if an extensive volume of gas was ignited in a commercial mine there would be little difference in effect whether the dust beyond was on the floor, ribs, or timbers.

DUSTS OF DIFFERENT SIZES ON FLOOR ONLY

A series of tests was started in 1926 to determine the explosibility of Pittsburgh coal dust of different sizes placed on the floor only, and the effect of adding coarse coal up to 1 inch in size to this dust. The explosions were initiated by source *B*. The first step was determination of the limits of explosibility of dust containing 10, 15, and 20 percent minus 200-mesh material placed at rates of 0.31 to 0.42 ounce per cubic foot. The limits were not determined closely but lay in the neighborhood of 30, 35, and 45 percent incombustible for the respective sizes. It is to be expected that the effect of concentration would be marked in these tests, but the work was not extensive enough to prove that these were the highest limits that could be obtained.

Coarse coal was added in three tests only, and the data are too fragmentary to be interpreted.

TESTS OF SEGREGATED DUST LOADINGS

Studies of explosion hazards in certain mines in Utah and Wyoming in 1925 showed that many haulageways required little timbering. They had been rock-dusted, but subsequent spillage of coal from cars had badly contaminated a strip about 5 feet wide along the track. In some cases the strip was watered with the idea of neutralizing the coal dust.

A series of tests was made with mine-size Pittsburgh coal dust in which these conditions were reproduced as closely as possible. In tests 680 to 682 the coal dust was spread over the entire floor, and shale dust was placed on the side shelves in successive amounts until, in test 682, it was 80 percent of all the dust present. The explosions were initiated by source *B*, and flame traversed the entire dust loading in each test. The coal dust was used without any shale dust in test 683, and the resulting explosion was not markedly different from those obtained when the shale dust was present. It was proved definitely that rock dust on the ribs cannot prevent propagation of flame through pure coal dust on the floor, a finding in agreement with those reported in preceding tables.

The next step was to restrict the coal dust to a strip 5 feet wide, such as was present in the mines investigated. A weight of shale dust equal to that of the coal dust was placed in the spaces between the strip and the ribs in test 692, and an explosion was not obtained, but the flame extended 200 feet in the entry and 375 feet in the air course. Additional shale on the side shelves shortened the flame in test 691, but it was still longer than would have been the case had the dusts been thoroughly mixed. It is evident that eddying of the air during the tests did not bring shale dust from the side shelves to the center of the entry, and its effectiveness was less because of this.

Similar tests made with coal from one of the Utah mines gave the same results.[37] It was also found that the strip of pure coal dust could be neutralized by watering, but the percentage of moisture required in the coal was larger than is likely to be maintained in a commercial mine. Prevention of spillage, together with efficient rock dusting, is the best method of handling this problem.

Three other tests of Pittsburgh coal dust were made in 1925 to determine the effect of additional dust on the cross shelves. The idea was to simulate conditions in a timbered entry which had been rock-dusted with subsequent deposition of coal dust on the rock dust on the timbers. Shale dust was placed on the cross shelves, and pulverized coal dust was spread over it. Explosions resulted in all three tests. In the last one (no. 695) the incombustible content of all the dust was 71 percent. The effect of distribution is very marked in this case; the mantle of pulverized coal dust over the shale dust on the cross shelves was primarily responsible for the propagation of flame. This emphasizes the need of preventing such coal-dust accumulations in timbered entries.

MACHINE DISTRIBUTION VERSUS STANDARD DISTRIBUTION OF DUST IN TESTS

Use of machines for rock-dusting mine entries is practically universal in this country. The distribution of dust effected in this manner is different from that used in Experimental mine work, and a few tests were made in 1925 to determine what differences in explosibility resulted. The machine used was of the fixed-discharge type and was loaned by the Pittsburgh Coal Co. The tests were made at the time of a special investigation of barriers in which that company cooperated and were not under standard conditions. Ignition was by source *C*, with the addition of pulverized coal dust in the test zones extending to E1200 and A1250. This gave flame to E1075 and A1050 with no other dust present. The dust under test was placed only to E950 and A950, as the test zone had not then been extended to E750 and A750. The test zone was too short for a source of such great strength and for this reason the results obtained are not considered generally applicable.

Four additional tests initiated by source *B* were made at a later date; the dust under test was placed to E950 and A950. In the first two of these (nos. 678 and 688) mine-size coal dust was premixed to contain 63 percent incombustible material and was distributed in the usual manner in the former and by machine in the latter test at the rate of 1 pound of coal dust per linear foot. Dust discharged from the machine would not stick to the cement-coated walls of the

[37] Greenwald, H. P., Explosibility of Coal Dust from Four Mines in Utah: Tech. Paper 386, Bureau of Mines, 1927, pp. 16–18.

test zone, and the quantity that came to rest on the cross shelves was small. Propagation was obtained with the standard loading, but not with the machine loading, due entirely to the better distribution of the dust by standard loading. Test 678 (standard loading) is reported in more detail in table 5, and the distribution of dust obtained in test 688 (machine loading) was much the same as in test 687, listed in table 5; the results of tests 687 and 688 were quite similar.

In test 689 the same quantities of shale and coal dust were run through the machine separately to give a coal-dust mantle over the shale dust. The result was nonpropagation, the same as when the dust was premixed. Finally, in test 690 the same quantity of shale dust was applied by the machine, and the coal dust scattered by hand on the floor only. Again the result was nonpropagation.

It does not appear proper to apply these results to commercial mines in which the rock-dusting machine usually causes a coating of incombustible dust to adhere to the walls and, to a smaller extent, to the roof. In such a case the dust is in position to be more effective. It is true, however, that a fixed-discharge machine is less likely to place a suitable quantity of rock dust on overhead cross timbers and to displace coal dust therefrom.

SUMMARY REGARDING EFFECT OF DISTRIBUTION OF DUST

It is possible to draw two general conclusions from the above tests of different distributions of dust:

1. Dust in all positions around the perimeter of a mine entry must be rendered inert, but the amount of incombustible material required to do this varies with the location, size, and quantity of the coal dust and with the dust-raising power of the source of ignition.
2. Dust on the floor can be of lower incombustible content than that on ribs and timbers, but the differences that can be permitted are not known with any degree of accuracy.

The need of additional testing is evident.

MISCELLANEOUS TESTS

This designation covers two minor groups of tests: (1) An investigation of the effect on explosibility of small changes in the minus 200-mesh dust content of Pittsburgh coal dust and (2) tests initiated by blow-out shots close to the portal of the main entry.

EFFECT OF SMALL CHANGES IN SIZE OF COAL DUST

Coal dust used in certain tests of barriers conducted in cooperation with Pittsburgh Coal Co. in 1925 contained 25 percent of minus 200-mesh material to reproduce exactly conditions observed at some points in one mine operated by that company. It was necessary to determine the explosibility of this dust compared with that of mine-size dust (20 percent minus 200-mesh). Three tests were made in February 1925. All were standard propagation tests of mixtures containing 35 percent of Pittsburgh coal dust and 65 percent of crushed shale dust. The proportion of minus 200-mesh material in the coal dust was 20, 22.5, and 25 percent in the respective tests. Propagation was not obtained in any test, but there was progressive lengthening of flame as the coal dust was made finer. The extreme differences were no greater than the error of duplicate experiments.

A change of 2.5 percent in the minus 200-mesh content of coal dust certainly has no effect on limits of explosibility, and it is doubtful if one can ascribe a definite effect to a 5 percent change. For practical purposes tests with dust containing 25 percent of minus 200-mesh material can be compared directly with those of dust containing 20 percent. Also a tolerance of 2.5 percent can be allowed when mine-size coal dust is prepared, and this lessens labor in preparing for tests.

TESTS INITIATED BY BLOW-OUT SHOTS NEAR THE PIT MOUTH

A study of the initiation of dust explosions near the entry portal was made in 1917, and test results were reported in Bulletin 167, page 348, table 41. Explosions of this character were used as demonstrations seven times during the present period, as follows:

Tests initiated near portal of main entry

Test no.	Date	Purpose	Number of spectators
872	May 7, 1926	Preliminary to test 873	----------
873	May 13, 1926	Demonstration for Mine Inspectors' Institute of America	250
878	Oct. 4, 1926	Preliminary to test 879	----------
879	Oct. 8, 1926	Demonstration for American Institute of Mining and Metallurgical Engineers.	300
888	Dec. 10, 1926	Demonstration for Coal Mining Institute of America	50
974	Aug. 31, 1927	Demonstration for International First Aid and Mine Rescue Contest	300
1066	Nov. 26, 1928	Demonstration for Second International Conference on Bituminous Coal	75

In the earlier work it was customary to try out the arrangements a few days before the demonstration to assure their success. Preparation for all these tests were alike in most respects. Initiation was by a blow-out shot of 4 pounds of FFF black blasting powder from a cannon placed on the floor at E180 and pointing outward. Eight hundred pounds of pulverized Pittsburgh coal dust were distributed over the first 400 feet of the main entry and were principally on temporary cross shelves sprung between the ribs close to the roof. Rock dust was scattered over the balance of the main entry to reduce violence and prevent the flame traveling too far into the mine beyond the test loading.

This arrangement produces a spectacular demonstration. The first projection of flame from the portal is due to combustion of the dust between the cannon and that point. At the same time flame is also traveling rapidly into the mine and a steady stream of dust and smoke is projected from the portal. This dust is fresh fuel for the flame outside, and the continued rush forces the flame front 300 to 500 feet from the portal. The temporary cross shelves are reduced to fragments and thrown out of the mine to rain down over a considerable area of the opposite hillside. Experience has shown that it is necessary to develop considerable pressure in the mine to obtain desired results outside, and, unfortunately, this causes destruction of side and cross shelves in the standard test zone. This type of demonstration is justifiable for educational purposes only when a large number of mining men wish to view such explosions.

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