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NOTES
ON
EXPLOSIVE MINE GASES AND DUSTS

WITH SPECIAL REFERENCE TO

EXPLOSIONS IN THE MONONGAH, DARR, AND NAOMI COAL MINES

BY

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NOTES ON EXPLOSIVE MINE GASES AND DUSTS, WITH SPECIAL REFERENCE TO EXPLOSIONS IN THE MONONGAH, DARR, AND NAOMI COAL MINES.

By Rollin Thomas Chamberlin.

INTRODUCTION.

CHARACTER OF THE REPORT.

The studies herein reported were begun as a part of researches undertaken by the United States Geological Survey looking to the more efficient utilization of the coal in the United States through the reduction of waste in its extraction, and were continued as part of further researches having regard to the conservation of the fuel resources of this country and to the lessening of injuries and fatalities in coal mining.

Among other phases of the general problem to be studied were the origin of the gas which escapes into coal mines, its modes of occurrence in the coal and rock strata, and the conditions governing its outflow into the mines. The subject of relative danger from destructive explosions due to gas and coal dust in different mines belonging to different coal fields was to be one of the principal lines of investigation.

But this work was barely under way when the series of unusually disastrous explosions in the Naomi, Monongah, and Darr mines of Pennsylvania and West Virginia, in December, 1907, afforded an exceptional occasion to observe the behavior of explosions on a large scale. Because of the opportunities for study afforded by these terrific explosions, the inquiry originally planned was diverted to the more specific investigation of the conditions in these mines, and the examinations have been directed toward finding those qualities of gas and dust which were concerned in these explosions. The following discussion, therefore, consists essentially of a report on that subject; but it is far from being exhaustive, and is to be regarded as a preliminary outline of investigations which are still in progress.

EXPLOSIONS STUDIED.

The first of the three mine explosions mentioned occurred in the Naomi mine of the United Coal Company, near Bellevernon, Pa., on Sunday, December 1, at 7.40 p. m. All the men who were within the mine at the time, fortunately only 34, were killed.

Less than a week later there occurred in mines Nos. 6 and 8 of the Fairmont Coal Company at Monongah, W. Va., the most disastrous mine explosion yet recorded in the annals of American mining. The mines were comparatively new and well laid out. Mine No. 8 had been in operation only about two years and was the pride of the Fairmont Coal Company. Mine No. 6 was first opened about four years earlier. In order to make it possible, in case of emergency, for either mine to be ventilated by the ventilating system of the other, the two sets of workings were connected underground. The F face heading of mine No. 6 led directly into No. 2 north heading of No. 8 mine. On Friday, December 6, at about 10.30 in the morning, an explosion of unusual violence swept completely through both mines, pursuing its course throughout the numerous ramifications and bursting out of the two pit mouths, located 1¼ miles apart, nearly simultaneously. The slope of mine No. 6 was only slightly damaged, but at the mouth of No. 8 the destruction was very great. The fan was wrecked, the engine house was demolished, and mine timbers were blown across Monongahela River. As nearly as can be determined, 361 men were killed in the two mines by the explosion.

While the inspection of the Monongah mines was still in progress, on Thursday morning, December 19, at about 11.20, a similar explosion wrecked the Darr mine of the Pittsburgh Coal Company at Jacobs Creek, Pa.; 238 men lost their lives in this explosion, which in number of casualties is second only to the Monongah disaster in the history of American mining. Of all the men in the mine at the time of the explosion, only one man, who happened to be within 100 feet of the surface on an old manway in a wet, unexploded portion of the mine, succeeded in escaping alive.

The underground investigation of these mines was made in cooperation with Clarence Hall and Walter O. Snelling, of the United States Geological Survey, and James W. Paul, now of the Survey but at that time chief of the department of mines for West Virginia, to all of whom the author is greatly indebted for valuable assistance, suggestions, and advice. Mr. Paul will report on the nature of these explosions, the precipitating causes, their destructiveness, and the general conditions in these mines following the disasters. The present report is confined essentially to the laboratory examination of some of the explosive materials collected from these mines directly after the explosions.

GASES FOUND IN THE MINES.

METHODS OF COLLECTING.

As soon as practicable after these explosions samples of the mine atmosphere were collected at the coal faces and from the return air ways in various parts of the mines. It was hoped that something as to the nature of the after damp might be determined, but as the exploration of the mines could be carried only where there had been a certain amount of ventilation, the samples of after damp were necessarily greatly diluted with air. With the aid of breathing helmets and compressed-air cylinders attempts were made to collect after damp in the tight places where there appeared to have been little ventilation, but the subsequent analyses have shown that the proportion of after damp remaining was small. Other samples were taken to determine the accumulation of fire damp in the workings.

The samples of air and gas from these mines were collected for analysis in glass tubes of 125 cubic centimeters capacity. These tubes were drawn out to a 5-millimeter bore at each end, over which was slipped a piece of red antimony rubber tubing 5 to 6 centimeters in length. Before entering the mine each tube was filled with water, and a tight-fitting plug of glass rod was inserted in the rubber tubing at each end. To take a sample of the mine air the glass plugs were removed from the ends of the tube, allowing the water to run out and be replaced by air, after which the ends of the tube were securely closed by the plugs and the rubber connections tightly wired with copper wire. Glass tubes thus sealed were found to hold gas samples for several weeks without apparent change from leakage or diffusion. However, as a thin film of water always remains upon the walls of the tube when the gas is collected in this manner, it is inevitable that a small amount of carbon dioxide be absorbed. Haldane[a] has called attention to the fact that when gas samples are collected in glass tubes whose walls are moist, a small amount of carbon dioxide is absorbed by the sodium silicate of the glass. If the water used be clear, the gas sample loses a small amount of carbon dioxide, but if the water used be dirty, the sample may gain carbon dioxide from the action of bacteria. The samples of gas collected in the Naomi, Monongah, and Darr mines are all subject to these criticisms. Clear water was used in every tube but one, No. 26, which had to be refilled from a pool of standing water in the mine. Whenever the sample could not be analyzed within a few days after it was collected, the rubber connections were completely coated with paraffin, thus preventing with certainty any passage of gas through the rubber.

The samples of gas obtained from these mines were for the most part selected either from points in the workings where there appeared

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[a] Foster, Sir Clement, and Haldane, J. S., The investigation of mine air.

to be unusual quantities of fire damp, or where the presence of after damp was suspected. Other samples were collected from the return air currents to obtain information upon the general character of the air throughout certain sections of the mines. Except in one or two special cases, the samples were collected just below the roof, in order to obtain a proportion of methane somewhat near the maximum present in the air. This was thought desirable because the gas near the roof would be most likely to be ignited from an open light upon a miner's cap, and because the maximum percentage of marsh gas in an entry gives the best indication of the danger from gas.

ANALYSES.

The analyses of the samples of gas collected within these three mines are given in the table which follows. The first 18 analyses were made according to the technical method of gas analysis described by Hempel.[a] The remainder of the analyses, with the exception of Nos. 23 and 29, were carried on over mercury in the apparatus devised by Professor Bone, of the University of Leeds.[b]

Analyses of samples of gas taken in Monongah, Naomi, and Darr mines.

[Figures give percentage.]

No.	Place.	Date.	CO_2.	CO.	C_nH_{2n}.	CH_4.	O_2.	N_2.
1	Monongah, mine No. 8; room 13 on fifth right, off No. 2 north heading	*1907.* Dec. 12	0.16	......	....	1.59	20.48	77.77
2	Monongah, mine No. 8; room 19 on fifth right, off No. 2 north heading	Dec. 12	.41	0.05	....	.85	19.44	79.25
3	Monongah, mine No. 8; return air way of fifth right, off No. 2 north heading, opposite room 15	Dec. 12	.63	.06	....	.09	19.82	79.40
4	Monongah, mine No. 8; No. 1 south heading, 350 feet inby third right	Dec. 12	.05	.02	....	....	20.55	79.38
5	Monongah, mine No. 6; H manway, 30 feet from coal face	Dec. 13	.10	......	....	.65	20.61	78.64
6	Monongah, mine No. 6; face of H entry	Dec. 13	.17	.05	....	1.23	20.24	78.31
7	Monongah, mine No. 6; face of No. 4 right heading, off F face entry	Dec. 13	.19	.02	....	.48	20.48	78.83
8	Monongah, mine No. 6; room 27 on fourth right, off F face entry	Dec. 13	.40	.07	....	8.37	18.40	72.76
9	Monongah, mine No. 6; main south return air way, 50 feet from bottom of shaft to fan	Dec. 16	.20	......	....	.22	20.40	79.18
10	Monongah, mine No. 6; main right return air way, 200 feet inby A face entry	Dec. 16	.18	.02	....	.45	20.33	79.02
11	Monongah, mine No. 8; face of north return air way to the mains	Dec. 17	.88	.21	....	1.35	19.43	78.13
12	Monongah, mine No. 8; face of left return air way of third north	Dec. 17	.54	.27	....	9.44	16.88	72.87
[c]13	Monongah, mine No. 8; room 27 on second left, off No. 2 north heading	Dec. 20	.42	.05	....	1.32	19.80	78.41
14	Naomi mine; face of right main	Dec. 14	.32	......	....	20.99	16.37	62.32
15	Naomi mine; face of entry 35	Dec. 14	1.15	.06	....	21.59	15.11	62.09
16	Naomi mine; main return air current, center main, 1,800 feet from mouth of slope	Dec. 14	.26	.02	....	.75	20.11	78.86
[c]17	Darr mine; left return air way just inside of first crosscut to left inby swamp entry	Dec. 21	1.07	.61	....	2.51	17.50	78.31
18	Darr mine; from same point as No. 17	*1908.* Jan. 1	.49	.01	....	1.50	19.67	78.33
19	Darr mine; return air current at first face entry 30	Jan. 1	.99	.25	....	1.14	18.06	79.56
20	Darr mine; from first left butt, 30 feet from entry 30	Jan. 1	.72	.18	....	1.55	18.64	78.91
21	Darr mine; main entry 5 feet inby third right crosscut, inby entry 30	Jan. 1	1.04	.08	0.02	4.99	17.59	76.28

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[a] Hempel, W. M., Methods of gas analysis, 1902: technical method.
[b] Bone, W. A., Jour. Soc. Chem. Ind., vol. 27, 1908, pp. 10–12.
[c] Collected by Clarence Hall.

Analyses of samples of gas taken in Monongah, Naomi, and Darr mines—Continued.

No.	Place.	Date.	CO_2.	CO.	C_nH_{2n}.	CH_4.	O_2.	N_2.
		1908:						
22	Darr mine; main entry, 20 feet inby fourth right crosscut, inby entry 30	Jan. 1	2.31	.28	0.31	6.01	14.09	77.00
23	Darr mine; return air from swamp entry south air way, first break through	Jan. 2	1.36	.02	....	.58	19.51	78.53
24	Darr mine; No. 12 right butt, off swamp entry 75 feet from face	Jan. 2	.67	.10	....	6.25	18.16	74.82
25	Darr mine; 20 feet from face of swamp entry	Jan. 2	1.45	......	.09	50.67	6.13	41.66
26	Darr mine; No. 12 right butt, off entry 27, 80 feet from face	Jan. 2	1.36	.11	....	4.24	16.41	77.88
27	Darr mine; mouth of drill hole in face of right air course of main entry	Jan. 3	1.37	.03	....	32.00	12.19	54.41
28	Darr mine; face of No. 12 right butt, off entry 27	Jan. 4	.59	.12	.09	7.99	17.57	73.64
29	Darr mine; from entry 30, 125 feet inby No. 1 left butt	Jan. 5	.79	......	....	2.12	17.61	79.48

METHANE.

It will be seen from the table that the highest percentages of methane (CH_4) were usually found in the samples collected at the faces of some of the mains. Methane in such high percentages occurred only more or less locally, either at the high points in the roof where, owing to its extreme lightness, it had accumulated, or as a thin stratum of fire damp floating along beneath the roof of an entry for a short distance from the coal face. Generally the diffusion of the gas was found to have taken place slowly in tight places where the current of air was slight, so that at a few rods from the face the percentage of methane in the air, even at the roof, was much reduced, while at the floor there was still less methane.

But in some places the gas was found to have become far more evenly distributed throughout the entries. In several of the entries in the Darr mine (see analyses 21, 22, 24, and 26) fire damp was detected in such quantities by the Wolf lamp, at distances of 75 to 100 feet from the coal face, that it was not thought advisable to push on to the faces even with safety lamps. Later, with an electric flash light to illumine the way, the faces of two of these three entries were visited. Tube 28, filled with air on January 4, 1908, from the face of No. 12 right butt, off entry 27, contained 7.99 per cent of methane, while tube 26, filled on January 2 at a point 80 feet from the face of this same entry, contained 4.24 per cent of methane. The conditions were similar at the face of the main entry. Tube 21, filled with air from the roof of the main entry, 5 feet inby the third right crosscut, inby entry 30, contained 4.99 per cent of methane, while tube 22, filled a few minutes later at a point 20 feet inby the fourth right crosscut (about 60 feet from the face of the main), contained 6.01 per cent of methane. Two days later a sample of gas (No. 27) was taken from the mouth of a drill hole 5 inches in diameter in the face of the right air course of the main entry. In this methane amounted to 32 per cent.

These figures show that the percentage of methane in the air near the roof of the gassy entries diminished rapidly with increasing distance from the face. This was true even in entries where the diffusion has been fair, for the Wolf lamp at the point where tube 21 was filled indicated gas as low as 2 feet above the floor. The high percentages of methane were chiefly local. The main return air currents, and in general those parts of the entries distant from the coal face, contained methane only in very much smaller proportions. In these passageways the gases had become more thoroughly mixed by diffusion as well as diluted in the draft of air, and hence here it made less difference whether the sample for analysis was collected at the roof or near the floor. An example of this was shown in No. 1 left butt, off entry 30, in the Darr mine. Tube 20, filled at the roof of the entry 20 feet inby from entry 30, showed only 1.55 per cent of methane. At this point a Wolf lamp on a tie showed a ¼-inch gas cap, indicating from 1 to 1.5 per cent of methane. As only a very slight current of air was moving out of this entry, the thorough mixing of the gases was apparently due largely to steady diffusion rather than to the air draft. Tube 29, filled with gas-laden air from the roof of entry 28, Darr mine, about 125 feet inby No. 1 left butt, contained 2.12 per cent of marsh gas. On the floor just below nearly a ⅓-inch gas cap was got with a Wolf lamp. The air was moving slowly.

In the main return air ways the fire damp was more diluted. On December 21, two days after the explosion in the Darr mine, when the ventilation was bad, the air from the return air way just inside of the first crosscut to the left, inby from the swamp entry, contained 2.51 per cent of methane (analysis 17); but the air at this same point on January 1, when the ventilation was better, contained only 1.50 per cent of marsh gas (analysis 18). On January 2 the return air from the swamp entry showed only 0.58 per cent of methane (analysis 23). Two days later a Chesneau lamp registered 1.4 per cent of fire damp where tube 18 had been filled, and 0.4 per cent in the return air from the swamp entry, indicating that, while there had been a slight improvement in the character of the air within these two days, the figures for tubes 23 and 18 are probably not far from the normal conditions. Where the Chesneau lamp registered 1.4 per cent of fire damp on January 4, and the chemical analysis of gas collected January 2 gave 1.50 per cent, the Wolf lamp on each occasion showed a ¼-inch gas cap.

In the Naomi mine, where very high percentages of methane were found at some of the entry faces, the main return air current on the center main, 1,800 feet from the mouth of the slope, contained, on the afternoon of December 14, 1907, only 0.75 per cent of marsh gas (analysis 16).

At Monongah there appears to be much less gas in the mines, both locally near the coal face, and in the return air in particular. In mine No. 6 the air of the main south return air way, 50 feet from the bottom of the shaft leading to the fan (analysis 9), and another sample from the main right return air way, 200 feet inby A face entry (analysis 10), contained, on December 16, 1907, only 0.22 and 0.45 per cent of methane, respectively. In mine No. 8 a test of the air collected on December 12 from the return air way opposite room 15 on the fifth right, off second north heading, showed only 0.09 per cent of methane (analysis 3). However, instead of collecting the gas from near the roof, the tube in this case was filled at a point about midway between the floor and the roof.

AFTER DAMP.

In all the samples of mine air collected in the Monongah, Naomi, and Darr mines within a few days after the explosions, the percentage of carbon dioxide greatly exceeded that of carbon monoxide. But it is true that none of these samples was collected until a fair state of ventilation had been reestablished after the explosions, such that parties could remain in the mines for several hours. The best of the samples was No. 17, taken from the Darr mine by Clarence Hall on the afternoon of December 21, two days after the explosion. While obtaining this sample three of the party were so overcome as to be forced to leave the mine. An analysis of this air showed 1.07 per cent of carbon dioxide and 0.61 per cent of carbon monoxide. No other sample approached this one in respect to the prominence of carbon monoxide, but even in this one the after damp was much diluted with air.

It may be instructive to undertake a rough calculation to show approximately what proportion of after damp is really present. Assume that essentially all of the oxygen of the air in the exploded portion of the mine was consumed in the explosion, and that carbon monoxide was formed because of insufficient oxygen, either directly or from the reduction of carbon dioxide by the floating particles of incandescent coal dust. Before making a computation of the proportion of after damp, it is necessary to decide to which of these reactions the carbon monoxide is to be assigned, as it makes a difference in the total resulting amount of carbon monoxide whether the monoxide be formed directly from the partial combustion of the gas or through the reduction by the glowing particles of coal dust of a portion of the carbon dioxide produced in the explosion.

Beard,[a] quoting Thomas, states that the explosion of a mixture of methane and air at the most explosive point (methane 9.57 per cent, air 90.43 per cent) produces no carbon monoxide, but that as

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[a] Beard, J. T., Mine gases and explosions, 1908, p. 130.

the percentage of methane is increased above the point named carbon monoxide is formed in ever-increasing proportion until, at what he gives as the explosive limit, 16.67 per cent of methane in air, the result of an explosion would be 87 per cent monoxide and 13 per cent dioxide; while near the limit of inflammability, 29 per cent methane, no carbon dioxide is formed. He writes the equation $2CH_4+O_2+4N_2=2CO+4H_2+4N_2$.

Agreeing with this in a measure is the statement of the French fire-damp commission that the explosion of a mixture of methane and air, containing 12 per cent of methane, gave rise to the following gases: Carbon dioxide, 4.8 per cent; carbon monoxide, 3.9 per cent; methane and other hydrocarbons, 2.5 per cent; hydrogen, 3.5 per cent; nitrogen, 82.2 per cent; total, 96.9 per cent.

At variance with this, Broockmann concludes from his own experiments with the products of combustion of methane and air that a pure fire-damp explosion gives no carbon monoxide.[a] A mixture of air and fire damp containing from 10.8 to 13.5 per cent of marsh gas he found to give two separate flames. Expecting to find some carbon monoxide formed as the result of the first flame, Broockmann removed the products of the first combustion, in an exploding mixture of methane and air, before the appearance of the second flame, but in no case found a trace of carbon monoxide. Instead, the heat of the first combustion converted the unconsumed methane into acetylene and hydrogen. These doubtless furnish the fuel for the second flame.

Heise and Herbst also state[b] that a pure gas explosion never produces carbon monoxide, and that an explosion of air containing more than 9½ per cent of methane produces, along with steam, only carbon dioxide. Differing somewhat with Broockmann, they state that the two elements, carbon and hydrogen, which are combined in CH_4 become separated only when sufficient oxygen is present for the complete oxidation of both elements. Otherwise the compound does not allow itself to be split up.[c]

For the computation in the case in hand (analysis 17) it will be assumed that the carbon monoxide has not been produced directly from a partial combustion of methane and other hydrocarbon gases, but has resulted from a reduction of the carbonic acid by the particles of incandescent coal dust, according to the reaction $CO_2+C=2CO$. The analysis of the return air showed 1.07 per cent of carbon dioxide. From this are to be deducted both the percentage of carbon dioxode in the air, 0.03 per cent, for the after damp has been much diluted since the explosion, and also the carbon dioxide exhaled from the coal during that time. A rough estimate of the latter can be made,

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[a] Broockmann, Niederrheinisch-Westfälischen Steinkohlenbergbaues, vol. 6, p. 52.

[b] Heise and Herbst, Bergbaukunde, vol. 1, 1908, p. 448.

[c] Idem, p. 463.

as the analyses of the gas issuing from the coal in the form of feeders and blowers, as well as from coal bottled in a vacuum, show that the proportion of carbon dioxide to methane in the gas escaping from the fresh coal of these mines is 1 or 2 to 100. As the percentage of methane was found to be 2.51, the amount of carbon dioxide which the fresh coal has contributed to the air since the explosion may be taken to be 0.03 per cent. This is the proportion of carbon dioxide to methane in the gas from fresh coal. In the older workings of the mine the proportion of the dioxide is greater than this; but in the absence of data upon the ratio of these gases escaping from coal which has long been exposed to the air, no allowance is here made for the greater proportion of carbon dioxide in the old entries. This leaves 1.01 per cent of carbon dioxide to be assigned to the after damp produced by the explosion.

To produce 1.01 cubic centimeters of carbon dioxide and 0.61 cubic centimeter of carbon monoxide from an explosion of methane, in cooperation with coal dust whose heated particles cause the formation of the monoxide by abstracting oxygen from a portion of the dioxide, 2.63 cubic centimeters of oxygen would be consumed, providing that all the hydrogen of the methane was burned to water.

This computation does not take into account the fact that, in addition to methane, other hydrocarbons participated in the explosion. These necessarily consisted of relatively more carbon than CH_4. But, on the other hand, the coal-dust particles which caused the reduction of the dioxide to the monoxide, instead of being pure carbon, contained a certain proportion of hydrogen, a portion of which was probably oxidized to water. These two factors tend to offset each other. Because of their complexity they can not be further treated here.

On the supposition that no carbon dioxide was absorbed by the water in the mine, and that all the oxygen in the air was consumed in the explosion, the volume of the oxides of carbon in the sample collected should bear the same relation to the amount of CO_2+CO originally developed by the explosion as the corresponding volume of oxygen, 2.63, does to 20.5, the percentage of oxygen which is assumed to have been originally present in the mine. This figure is taken because the coal rapidly absorbs oxygen from the air. The average proportion of oxygen in the air of tight places in this mine was found by a calculation from the analyses to be only 20.08 (see p. 15); but 20.50 would seem a better figure for the average of the mine air as a whole. The ratio $\frac{2.63}{20.5}$ is equal to 0.128, or from 12 to 13 per cent of after damp in the sample collected.

However, this can at best be only a rough estimate, as several uncertain factors are involved. The mine air previous to the explosion contained a small and unknown quantity of carbon dioxide. But on the other hand, some carbon dioxide has doubtless been absorbed by the water in the mine since the explosion. In a measure these factors tend to offset one another. It is also true that other hydrocarbons, in addition to methane, were consumed in the explosion, and these would unite with oxygen in different proportions. But methane in all probability contributed most.

While this sample of the air from the Darr mine after the explosion shows that carbon monoxide may reach a considerable percentage in after damp, the other samples of the mine air which, however, were collected after better ventilation had been established, showed the presence of much less carbon monoxide, even though the proportion of the dioxide in some samples amounted to 1 per cent. It seems probable that some and perhaps most of the difference was due to more thorough ventilation before the later samples were collected, for carbon monoxide, once removed, would not be resupplied except in very small quantities, but carbon dioxide might have been supplied from the coal, the lamps, etc., since the explosion.

However, the relative proportions of carbon dioxide and carbon monoxide in after damp must always be variable, depending on the ratio between the available oxygen and the available combustible matter, gas and dust, in the air. If the explosion were due largely to methane in the air, in quantities not exceeding 10 per cent, and with little dust as an accessory, little carbon monoxide would be formed. But, on the other hand, in a dust explosion where large quantities of coal dust are present, capable of distilling volatile hydrocarbons in volumes too great to be entirely consumed by the quantity of oxygen in the mine air, and where there is an abundance of hot coal dust stirred up in the air, carbon monoxide might, perhaps, be produced in greater quantities than the dioxide. A coal-dust explosion is more complex than one of fire damp. If the explosion of the dust proceeds by rapidly feeding the flame with combustible gases and hydrocarbon vapors derived from it through the influence of the heat, as is believed to be the case, there is, at first, sufficient oxygen at hand to insure the complete oxidation of the gases developed. Carbon dioxide and steam result. But under ordinary conditions, with plenty of dust, the distillation of volatile matter continues, liberating an excess of readily available combustible gas which, because of insufficient oxygen, is only partly consumed. In the absence of oxygen, a portion of the carbon dioxide already produced is reduced to carbon monoxide in variable proportions, depending on the amount of red-hot dust floating in the atmosphere and the length of time during which the dust remains sufficiently heated to allow the reducing reaction to proceed.

DEFICIENCY OF OXYGEN.

In order to ascertain the character of the mine air, irrespective of the after damp, a recalculation of the analyses was made. The analyses of gas from mine feeders and from coal bottled in a vacuum show that the proportion of carbon dioxide to methane in the gas escaping from the fresh coal of these mines is 1 or 2 to 100. Wherever methane is found in the mines it is safe to assume that a volume of carbon dioxide corresponding to 1 per cent of the methane has escaped from the coal simultaneously with the marsh gas. This figure, plus the 0.03 per cent of carbon dioxide in normal air, is subtracted from the percentage of carbon dioxide in the analysis. To be on the right side, it is assumed that all the rest of the carbon dioxide has been produced by the oxidation of CH_4, as the combustion of this compound consumes more oxygen per unit of carbon dioxide formed than any of the other compounds which could have participated in the explosion. The amount of oxygen which would have been required, on the basis of an explosion of methane, to yield the oxides of carbon found in the analysis, is then added to the percentage of oxygen shown by the analysis. The percentage of methane in the analysis, plus the carbon dioxide of normal air and that which, on the basis of the methane present, has been considered to have been derived from the coal since the explosion, is deducted from the total, and the remaining figures recalculated so as to add to 100.

This gives an estimate of the percentage of oxygen in the mine air irrespective of the after damp from the explosion and the feeder gas which has escaped into the workings from the coal since the explosion. Because of the assumptions, these estimates give a generous figure for the percentage of oxygen. An average of the three analyses of air from the Naomi mine made in this way was 20.86 per cent, eleven analyses from the Monongah mine gave 20.72 per cent oxygen, and thirteen analyses from the Darr mine gave an average of only 20.08 per cent oxygen. These figures indicate a deficiency of oxygen in the mine air which can not be attributed to the formation of free carbon dioxide or carbon monoxide, unless it be supposed that much of the carbon dioxide formed has been absorbed by water in the mine, which seems improbable in these dry mines. Instead, it would appear that the coal has absorbed oxygen from the air, thus reducing the percentage of that gas and increasing that of nitrogen.

The greatest deficiency in oxygen occurred in the sample of gas-laden air collected near the face of the swamp entry in the Darr mine (analysis 25). Corrected for carbon dioxide and methane, this sample showed the unusual proportions, oxygen 16.13 per cent and nitrogen 83.87 per cent. This sample was also characterized by the highest proportion of methane (50.67 per cent) obtained in these mines. That the diffusion of the air and gases in this cleft in the roof had progressed slowly is shown by the accumulation of so much fire damp, and it was apparently because of the stagnancy of the air in this nook that the coal was able to abstract such a proportion of the oxygen. It must be noted that feeder gas often contains several per cent of nitrogen, so that with 50 per cent of methane (feeder gas) present in the air a part of the apparent excess of nitrogen and deficiency of oxygen may, perhaps, be explained by this nitrogen coming from the coal.

As many of the samples of air which have contributed to these averages, particularly those from the Darr mine, were collected from sheltered, poorly ventilated nooks in order to get data on the accumulation of fire damp, the low figure of 20.08 per cent for oxygen is not representative for the air of the mine as a whole. While the loss of oxygen is less conspicuous in the general mine air than in pockets in the roof and in tight places where there is little air stirring, its effect is felt throughout the mine, and furnishes an additional reason for ventilation which will afford a continuous supply of good air, as well as remove the dangerous fire damp and the noxious products of combustion.

POSSIBLE CONDITIONS OF GAS IN COAL.

The gas which escapes from coal may exist within the mass of the coal in three possible conditions. It may be mechanically held or imprisoned in minute pores, cavities, or cracks throughout the coal; it may be occluded or dissolved within the substance of the coal; or it may be the result of slowly operating chemical reactions, such as those which have produced the coal from the original vegetable matter and which, still operative, might, as a working hypothesis, be supposed to generate gas in proportion as it is given off. In the first two cases the gases are supposed to be already existent within the coal as gases; under the third hypothesis they are to be regarded as now produced for the first time by chemical decomposition of the solid coal substance. The ultimate source of the gases may be taken as the same under each hypothesis, for there can be little doubt that the bulk of the gas given off from coal has arisen from the slow decomposition of organic matter as a by-product in the process which has converted vegetable humus into coal. The first hypothesis favors the belief that the gas-generating process has been very slow and that such gas as comes off at the present time has long been stored in minute cavities or pores, from which it escapes when the coal is fractured, as in mining operations. The second hypothesis assumes, like the first, that the gas was developed long ago, but differs from it in assuming that the gas, as fast as it was developed from the coaly matter, was retained within the coal substance in solution, or occluded, instead of being held mechanically in minute crevices and cracks. This hypothesis is suggested by the well-known property of various metals to occlude or dissolve within their mass certain gases, and by the familiar power of charcoal to condense on its surface or absorb many times its own volume of various gases. The term occlusion, which Graham gave to this imperfectly understood property of certain metals to absorb particular gases, has been very loosely used, especially in mining literature, where "occluded gas" usually means gas held according to either of the first two hypotheses, the radical difference between them having generally been overlooked. By some writers, indeed, the term is intended to carry the idea of the first hypothesis alone, the second, that of true occlusion, being left out of account.

The third idea is only a working hypothesis which is framed to recognize the possibility that the coal-forming, gas-generating process is still in progress, and that the escape of the gases is a sort of index of the present chemical activity within the coal.

LIBERATION OF GAS BY CRUSHING COAL.

PLAN OF EXPERIMENTS.

To throw light on this possible threefold state in which the gases are held in coal, and to determine the relative importance of the three hypotheses, a series of experiments was devised. In the first the coal was broken up and crushed to a coarse powder in an air-tight receptacle, from which any gas liberated during the process of crushing can be extracted by a vacuum pump. Only such gas as was already stored in the coal can be freed by crushing it, as the process is accomplished very quickly. How much gas might be expected to be freed from a state of true occlusion by crushing is less clear. The most thoroughly studied form of occlusion is that of hydrogen by palladium. Whether palladium charged with hydrogen will give off part of its gas at the ordinary temperature when placed in a vacuum depends entirely on the condition of the metal. If the palladium is in a very finely divided state, a considerable portion of the hydrogen is given off when the pressure is greatly reduced;[a] but the cast or forged metal gives off no hydrogen whatever when placed in a vacuum at ordinary temperatures.[b] The hydrogen begins to be evolved from the solid metal only at temperatures above 100° C. It is conceivable that reducing the size of coal fragments by crushing in a vacuum might, in some similar way, allow the evolution of gas which was not possible from the lump coal. But as the lumps of coal are only crushed down to a coarse powder it would not seem as if truly occluded gas should

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[a] Moissan, Chimie minérale, vol. 5, p. 860.

[b] Graham, Chemical and physical researches, pp. 283-290.

be freed, to any large extent, by the coal crusher, even in a vacuum. If crushed under full atmospheric pressure in an inert gas, no occluded gas should be liberated. It is not at all certain that coal behaves like palladium in these matters. It seems, therefore, safer to conclude that by crushing the coal and opening up many pores and cavities it is chiefly the imprisoned cavity gas that is liberated.

METHOD OF CRUSHING.

The apparatus for crushing the coal was constructed on the principle of the familiar steel mortar, fitted with a long piston rod incased in a heavy rubber tubing, which, with one end fastened to a flange at the top of the mortar cylinder and the other wired to the piston rod near its free end, makes an air-tight connection, and at the same time renders the piston movable. A few vigorous blows delivered with a heavy mallet upon the end of the piston rod serve to crush the coal, after which the gas liberated during the crushing is pumped out of the cylinder through a short delivery tube, fitted with a stopcock.[a] The apparatus is intended to maintain a complete vacuum for the short time required to crush a sample of coal, but in practice it was found advisable, in order to prevent a slight inleaking of air, to place the cylinder of the crusher in a pail of water during the operation. This crusher was able to pulverize from 50 to 100 grams of coal at a time. The coal was crushed both in a vacuum and under full barometric pressure.

DETAILED RESULTS.

Sample 1.—Coal collected on December 13, 1907, from the face of No. 4 right entry, off the F-face heading, mine No. 6, Monongah, was crushed in a vacuum on January 27, 1908. Starting with lumps of coal of about 1 cubic inch, the material was crushed twice, the crusher being opened after the first crushing and the finer dust sifted out. The extent to which the coal was reduced after both crushings was determined by sieves, as follows: Of 100.21 grams of coal used, 20.56 grams passed through a 30-mesh sieve, 31.26 grams passed through a 10-mesh sieve, and 48.39 grams was too coarse to pass the 10-mesh sieve. There was obtained 10.57 cubic centimeters of gas at 0° C. and 760 millimeters pressure, having the following composition:

Analysis of gas obtained by crushing coal sample 1.

	Per cent.
Carbon dioxide	2.90
Methane	39.65
Oxygen	10.07
Nitrogen	38.11
Nitrogen (excess)	9.27
	100.00

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[a] This rock crusher has been described in detail, with a diagrammatic sketch in The gases in rocks: Carnegie Institution of Washington, Pub. No. 106, p. 39.

If the gas all came from the coal which passed through the 30-mesh sieve, the methane would amount to 0.26 of the volume of that coal. But if to this coal be added that which passed the 10-mesh sieve, the methane is only 0.10 of the volume. The latter figure is to be preferred.

Sample 2.—Coal collected December 12, 1907, from room 3 on third right, off second north heading, mine No. 8, Monongah, was crushed in a vacuum January 28, 1908. Two lumps of coal were pulverized, in two crushings, to the following degree of fineness: Of 49.13 grams in all 20.24 grams passed through the 30-mesh sieve, 23.67 passed through the 10-mesh sieve, and 5.22 grams was too coarse to pass the 10-mesh sieve. The crushing liberated 11.71 cubic centimeters of gas at 0° C. and 760 millimeters pressure, which had the following composition:

Analysis of gas obtained by crushing coal sample 2.

	Per cent.
Carbon dioxide	1.56
Methane	40.99
Oyxgen	9.86
Nitrogen	37.62
Nitrogen (excess)	10.27
	100.00

The quantity of methane is equivalent to 0.30 of the volume of the coal which passed the 30-mesh sieve, to 0.14 of the volume of the 10-mesh coal, and to 0.12 of the volume of all the coal used.

A duplicate test with this same sample of coal, crushed in three trials, afforded the observation that there is not any very noticeable slackening in the gas obtained from the second and third crushings. For the first trial the total weight of coal is used. After the gas has been pumped over into the receiver, the crusher is opened and the fractured coal sifted with both the 10-mesh and 30-mesh sieves. Only the coal coarser than the 10-mesh sieve is returned to the cylinder of the crusher for the second trial. The second trial thus crushes coal fragments averaging about the size of a bean to fine 10-mesh coal and dust, and as it crushes about the same weight fine enough to pass through the sieves as did the first trial, it is to be expected that about the same volume of methane will be obtained. After the second trial the coal is again sifted and that portion which is too coarse to pass through the 10-mesh sieve is put back into the crusher for the third trial. It is clear that some of the gas comes from that coal which is partly crushed, though not fine enough to go through the 10-mesh sieve, but in estimating the volume of gas given off per unit volume of coal it seems advisable to consider only that coal which has passed through the sieves, for whatever gas may have come from the coarser coal would undoubtedly be offset by the gas still remaining in the fine coal. Crushing coal to 30-mesh does not remove all the gas.

In the experiments with samples 1 and 2 the coal was crushed in a vacuum and the gas brought out under reduced pressure. To ascertain the part played by low pressure in this process of gas extraction, and hence whether much gas escaped from occluding bonds, samples of coal were crushed under the full barometric pressure, both in air and in an atmosphere of carbon dioxide.

Sample 3.—Coal from the same can as sample 1 (p. 18) was crushed in air under full barometric pressure. As it was necessary in this experiment to discover how much methane is liberated solely by crushing the coal, without the cooperation of a reduction in pressure, the gas was removed from the crusher in two portions. The first portion consisted of the air and gas which was removed by the first stroke of the vacuum pump. The stopcock being open only about two seconds, and only about half the contents of the crusher being removed, whatever methane was found in this portion must have been freed from the coal without the influence of reduced pressure. As soon as this portion could be stored away for analysis, the remaining gas was rapidly pumped out of the crusher. These two portions were analyzed as follows:

Gases removed after crushing coal sample 3 in air, with their relation to the coal by volume.

Gas.	First portion.			Second portion.		
	Per cent.	Ratio to volume of coal as 1.		Per cent.	Ratio to volume of coal as 1.	
		30-mesh.	10-mesh.		30-mesh.	10-mesh.
Carbon dioxide	0.16	0.016	0.007	0.27	0.026	0.012
Methane	3.68	.35	.17	4.61	.45	.21
Air	96.16	9.31	4.34	95.12	9.23	4.31
	100.00	9.68	4.51	100.00	9.70	4.53

As would naturally be expected, the percentage of methane is higher in the second portion than in the first, though the difference is not great. But the greater amount of methane in the second portion was not liberated entirely through the influence of reduced pressure, as the fine coal had stood longer in the second case than in the first, and the element of time proves to be an important factor in the escape of gas from coal.

However, only the first portion is to be taken as representing the gas liberated during the crushing under full atmospheric pressure. An estimate of the total volume of gas obtained from the crusher on the basis of the analysis of the first portion gave the first two columns of the following table. A comparison of these figures with those in the last two columns, obtained by combining the volumes of the two portions analyzed separately, may help to show how much gas may be attributed to the reduced pressure.

Relation to the coal by volume of gases removed after crushing coal sample 3 in air.

[Ratio to volume of coal as 1.]

Gas.	Estimate based on first portion.		Total for the two portions as analyzed.	
	30-mesh coal.	10-mesh coal.	30-mesh coal.	10-mesh coal.
Carbon dioxide	0.031	0.014	0.042	0.019
Methane	.71	.33	.80	.38
Air	18.65	8.69	18.54	8.65
	19.39	9.03	19.38	9.04

The confirmatory tests were made with other samples of coal from Monongah mine No. 6. Sample 4 was collected December 16, 1907, from the face of the east returning air way, and crushed March 10, 1908. Sample 5 was collected December 13, 1907, from the face of the H manway, and crushed March 18, 1908. Each of these samples was crushed in air under barometric pressure, and the gas removed in two portions. For each sample the total volume of methane was calculated for both portions of gas, on the basis of the analysis of the first portion, which came over with the first stroke of the pump. At least this calculated amount of methane must have come off without the aid of reduced pressure. Expressed in terms of the volume of coal which was crushed down to 30-mesh, the amount for sample 4 was 0.27, and for sample 5, 0.79. The volume of methane actually obtained for the two portions was, in the same terms, 0.41 for sample 4 and 0.86 for sample 5.

In the test of sample 5 the difference between the total volume of methane actually obtained and the calculated volume which must certainly have been liberated from the coal under full barometric pressure is small. Moreover, only a portion of this small difference can be attributed to the effect of reduced pressure, as other factors, such as slow diffusion and the greater interval of time, have helped to cause this difference.

For a series of systematic experiments to show the amount of methane which is liberated from the same coal under various conditions, the can of coal which was collected from the face of the H manway in Monongah mine No. 6 was selected (sample 5). The results of crushing lumps of this coal are as follows, the several tests being set forth in numbered paragraphs, with the volume of methane expressed in terms of the volume of coal crushed to 30-mesh and to 10-mesh:

1. Coal was crushed in a vacuum, but so much water vapor was given off and drawn past the calcium chloride drying tube into the pump that in order to draw over all the gas it was necessary to keep the pump going for nearly one hour. Hence the time factor enters here. Ratio, by volume, of methane to 30-mesh coal, 0.88; to 10-mesh coal, 0.33.

2. Coal crushed in a vacuum and the gas immediately pumped off. Then a full atmosphere of carbon dioxide was run in and pumped out, bringing with it the last traces of methane. Two separate trials were made, giving ratios of 0.89 and 0.83, respectively, to 30-mesh coal, and 0.38 and 0.34 to 10-mesh coal.

3. Coal was crushed in a vacuum, but phosphorus pentoxide was used as a drying agent instead of calcium chloride. Ratio of methane to 30-mesh coal, 0.84; to 10-mesh, 0.33. After pumping out this gas and removing it for analysis, an atmosphere of carbon dioxide was run in as rapidly as the apparatus could be manipulated, and then pumped out again quickly, and the gas collected over a 30 per cent solution of potassium hydroxide. More methane came over, some, and perhaps most, of which is to be explained by the time consumed in the carbon dioxide treatment. The amount was 0.14 of the volume of 30-mesh coal, and 0.05 of the 10-mesh coal.

4. Coal crushed in air under barometric pressure. This test has been described on page 21 (sample 5). The amount of methane was 0.86 of the 30-mesh coal and 0.41 of the 10-mesh.

5. Coal crushed under barometric pressure in an atmosphere of pure carbon dioxide. Amount of methane, 0.91 of the 30-mesh coal, 0.44 of the 10-mesh.

Tests 6 and 7 were made to determine the influence of the length of time during which the coal is allowed to stand after crushing, upon the quantity of gas given off.

6. Coal crushed in a vacuum and allowed to stand 3½ hours with occasional pumping. Then the apparatus was filled with carbon dioxide and pumped out again. Total duration of the experiment, 4 hours; considerably more gas was thus obtained than when the process was completed in less than 1 hour. Analyzed in four separate portions. The total methane was 1.38 times the volume of 30-mesh coal, and 0.57 of the 10-mesh.

7. Coal crushed in a vacuum. Pumping kept up for 1 hour; then, after a short time, 30 cubic centimeters of hydrogen were let in and soon pumped out. After another 1½ hours an atmosphere of carbon dioxide was run in and pumped out again. Duration of experiment, 4 hours. Analysed in three portions. Total methane, 1.39 times the volume of 30-mesh coal, and 0.53 of the 10-mesh.

These last two experiments, in which the totals include all the methane which escaped from the coal during four hours after the process of crushing, show that the gas does not all escape from the coal within the first few minutes after the coal is shattered, and that to obtain comparative results it is necessary that the time consumed during the process of removing the gas after the coal has been crushed be approximately the same in all tests. In the last test the gases pumped off during the first hour, those brought over by the hydrogen, and those which came with the carbon dioxide, were collected and analyzed separately, but nothing of significance was developed except, perhaps, the fact that the hydrogen treatment yielded somewhat less methane than had been anticipated.

These experiments, taken as a whole, appear to indicate that, in respect to the volume of methane obtained from the coal, it makes little difference whether the coal is crushed in a complete vacuum, or under the full barometric pressure, in an atmosphere either of air or of carbon dioxide, provided the gas in each case is quickly pumped out of the crushing apparatus. Gas continues to escape from the crushed coal at a rather rapid rate for some time after it has been crushed, but this feature will be considered elsewhere.

The quantity of gas immediately liberated from the coal when it is broken up is thus largely independent of the outside pressure. Such gas, therefore, can not be supposed to have come directly from a state of occlusion, for, without an appreciable change either of temperature or pressure, occluded gas should not be given off in this way, even from finely divided coal. Nor can it come immediately from chemical decomposition of the nongaseous constituents of the coal. It must, instead, have been already stored within the mass of the coal as free gas, mechanically imprisoned in numerous pores, cavities, and crevices, from which much of it is immediately released as soon as the confining walls are shattered in the process of crushing, and the pores and cavities opened to the surface. Necessarily, in the process of crushing to this state of fineness, only a portion of the gas-holding pores are so opened as to enable the inclosed gas to escape at once. In many others, the shattering makes it possible for the gas to escape by slow diffusion, where before it was securely held. Hence an abnormally rapid escape of gas follows for a short period of time after the coal has been crushed.

However, it is not impossible that in those tests in which the coal was crushed in a vacuum or practical vacuum, the reduced pressure, acting on the fresh surfaces of the crushed coal, might have caused the escape of some truly occluded gas. If such gas escapes from the coal, it would be likely to come largely from that portion which was most finely pulverized. (See p. 17.) But quantitatively this occluded gas can not play a very important part in the gas liberated by crushing the coal, as its liberation is dependent on a reduction of pressure, and these experiments indicate that, in the volume of gas given off, it makes little difference whether the coal is crushed under the full barometric pressure or in a complete vacuum. Thus, while there is a possibility, and even a probability, that some of the gas does come from a state of occlusion, it seems more plausible to regard the main bulk of the gas escaping from coal during the process of crushing, and at an abnormal rate just after being crushed, as being cavity gas, whose escape is facilitated by the shattering which the crushed coal fragments have received. The fact that the presence of oxygen, nitrogen, hydrogen, or carbon dioxide in the crusher has little influence on the amount of methane given off during the crushing, and for a short length of time afterwards, is in harmony with the theory that this gas escapes largely from mechanical bonds.

GASES FROM COAL BOTTLED IN A VACUUM.

VACUUM BOTTLES.

The experiments with the coal crusher have shown how much gas can be liberated from these coals by crushing them to a certain degree of fineness and opening up many of the gas-holding pores. But this process does not remove all the gas, nor is it the only way to extract the gas from coal without the use of heat. To get the gas which slowly escapes from coal, different samples of coal were stored in vacuum bottles, from which the gas evolved was pumped out from time to time. Each of these bottles had a capacity of 500 cubic centimeters and was fitted with a one-holed rubber stopper containing a short delivery tube. Over the free end of the delivery tube was slipped a short piece of heavy antimony rubber pressure tubing, which serve to make the connection with the mercury pump. A strong screw clamp on the rubber tubing closed the way to the bottle. The stopper and rubber connections were all coated with paraffin to prevent leakage of air. When the air from the bottle had been completely exhausted, the clamp upon the rubber tube was tightly screwed, the rubber tube disconnected from the pump, and a plug of glass rodding quickly run into the rubber tube as far as the screw clamp would permit. Rendered tight by paraffin the bottle was submerged in a jar of water until the time came to remove the gas. At any time desired the bottle could be connected with the mercury pump and the gas which had accumulated removed for analysis, after which the bottle was again submerged in the water jar.

VOLUME OF GAS.

The volume of the gas extracted from coal by allowing it to remain in an essential vacuum for a period of time was somewhat variable and depended on the sample of coal, the interval of time between its removal from the coal seam and its confinement in the vacuum bottle, the size of the coal fragments, and the duration of the experiment. The finer the coal the more rapidly and completely was the gas liberated in a given period of time. At the end of six months gas was still accumulating steadily in those bottles which contained lump coal, and it was only in those containing crushed coal that the escape of gas had nearly ceased. The volume of gas from the crushed coal ranged from 0.9 to 2.3 times that of the coal from which it came. The lump coal yielded gas to the extent of 0.5 to 0.9 of its own volume during half a year at low pressure. Because of the pressure of other laboratory experiments, and the time required for the inspection of the Darr mine shortly after the material was collected at Monongah, more than a month elapsed between the collection of the coal samples and the bottling of them in a vacuum. These figures, therefore, do not represent all the methane given up by the coal since its removal from the seam, for a certain quantity of the gas may be supposed to have escaped while the coal was in the collecting cans.

To obtain data on the volume of gas lost during the first month after the removal of the coal from the seam, samples of fresh coal were collected in the usual cans, which were at once hermetically sealed with a thick coating of paraffin, before leaving the coal face. When opened in the laboratory about a week later, a determination of the gas in the cans was made, after which some of the coal was immediately placed in the vacuum bottles. In this way all the gas escaping from the coal after the sample was mined at the working face was determined. A specimen of bituminous coal in the form of lumps from the Mansfield mine at Carnegie, Pa., gave off 0.55 of its volume of gas, exclusive of nitrogen, during seven days in the collecting can and thirty days in the vacuum bottle. Analyses made at intervals during this length of time indicated that gas was freed much more rapidly during the first few days after collecting than later. But a similar experiment with gassy anthracite coal showed only a slight slackening in the rate of methane escape, and this change in the rate was almost uniformly distributed throughout the period of observation.

CHARACTER OF GAS.

The coal thus bottled in a vacuum was kept under observation for a period of half a year, during which time the bottles were connected with the mercury pump at stated intervals and the gas which had accumulated was removed for analysis. Thus not only was the rate at which the gas escaped from the coal discovered, but the character of the gas evolved throughout this length of time was determined. However, as the principal object of the experiments in which these vacuum bottles were employed was to determine the volume of methane escaping from the coal during a given interval of time, less care was given to the determination of the minor constituents, especially carbon monoxide and the ethylene series. In some tests the absorption of the olefins with fuming sulphuric acid, or bromine water, was omitted, and the gases of this series were removed, together with carbon monoxide, by cuprous chloride. Also, the leakage of small quantities of air into the vacuum bottles was not prejudicial to the chief purpose of the experiments, for the volume of methane was in no way affected. Although these analyses are subject to these limitations, they yet serve to indicate pretty closely the general character of the gas which escaped from the coal during the period of half a year under reduced pressure. Four of these sets of analyses of the gas from coals are given in the table following.

Analyses of gases escaping from small lump coal bottled in a vacuum, with relation to the coal by volume.

[Figures of analyses show percentage.]

EXPERIMENT A.[a]

Gas.	3 weeks after bottling.	4 weeks later.	10 weeks later.	9 weeks later.
Carbon dioxide	2.07	3.00	2.72	2.95
Carbon monoxide Olefins	.32	.07	.65	.84
Paraffins	35.51	69.10	76.05	84.38
Air: Oxygen	.39		.08	.38
Air: Nitrogen	1.47		.30	1.44
Nitrogen (excess)	59.77	27.83	20.20	10.01
	100.00	100.00	100.00	100.00
Relative volume	.17	.11	.13	.09

[a] Coal from the face of the east return air way in Monongah mine No. 8. The rate of the escape of the gas from this coal is expressed by curve 5 in fig. 1.

EXPERIMENT B.[a]

Gas.	3 weeks after bottling.	4 weeks later.	10 weeks later.	9 weeks later.
Carbon dioxide	1.05	0.83	0.63	0.60
Carbon monoxide Olefins	1.03	.29	.84	1.13
Paraffins	55.37	84.96	91.39	87.89
Air: Oxygen	.51	.35	.50	.40
Air: Nitrogen	1.91	1.32	1.89	1.51
Nitrogen (excess)	40.11	12.25	4.75	8.47
	100.00	100.00	100.00	100.00
Relative volume	.21	.20	.28	.21

[a] Coal from the face of the right main in Naomi mine. The rate at which this coal evolved gas is given by curve 6, fig. 1.

EXPERIMENT C.[a]

Gas.	First 10 days.	Second 10 days.	Third 10 days.
Carbon dioxide	8.88	13.52	12.34
Carbon monoxide			.22
Olefins		.82	
Paraffins	82.00	72.15	84.44
Air: Oxygen	.55	1.35	.58
Air: Nitrogen	2.08	5.11	2.19
Nitrogen (excess)	6.49	7.05	.23
	100.00	100.00	100.00
Relative volume	.31	.15	.12

[a] Coal from the face of room 21, on No. 4 southeast butt, off No. 6 face entry, Mansfield mine at Carnegie, Pa.

EXPERIMENT D.[a]

Gas.	First week.	Second week.	Third week.	Fourth week.
Carbon dioxide	0.02		0.17	
Carbon monoxide				
Olefins	.51	0.78	.87	0.29
Paraffins	86.86	93.99	94.19	98.58
Air: Oxygen	.04			.07
Air: Nitrogen	.15			.26
Nitrogen (excess)	12.42	5.23	4.77	.80
	100.00	100.00	100.00	100.00
Relative volume	1.22	.99	.89	.81

[a] Anthracite coal from the face of slope of gangway east of No. 30 tunnel, No. 1 north shaft, at Nanticoke, Pa.

The analyses of the gas from the other samples of Carboniferous coal which were subjected to this same treatment show similar results.[a] The most noteworthy change in the nature of the gas escaping from the coal during the period of observation was the steady decrease in the proportion of nitrogen and the corresponding increase in the percentage of methane. Much of the nitrogen that appeared in the portion of gas removed from the bottles at the end of the first three weeks doubtless came from air which adhered to the coal or was absorbed by its mass, and was not given off immediately when the vacuum was produced. As the oxygen which coal absorbs enters rapidly into chemical union with the substance of the coal, the latter respires chiefly nitrogen (with some carbon dioxide) in place of the air taken in. The influence of the nitrogen from the air is naturally most felt during the early part of the sojourn of the coal in the vacuum bottles, as this nitrogen is largely held by the surface layers or in the more prominent crevices and lines of fracture. It therefore escapes from the coal more readily than the gas originating in the coal, which is distributed throughout its mass, but most abundantly in the interior of the fragments, from which escape is slow and difficult. As this extraneous nitrogen was removed, the percentage of the methane rose proportionately.

Methane was quantitatively by far the most important gas which escaped from the bottled coal. After the extraneous nitrogen had been removed, it ran in some tests as high as 98 per cent of all the gas coming from the coal. More commonly, however, it constituted from 80 to 95 per cent of the gas liberated. Methane reached its highest percentage in the gas from anthracite coal, which yielded only small proportions of the other constituents, carbon dioxide and nitrogen.

In addition to methane, at least one other higher member of the paraffin series was found. In nearly every analysis the explosion of the residual gas with oxygen, after the removal of the absorbable gases, produced carbon dioxide in slight excess over what would have resulted from the combustion of methane alone. Calculations show that the excess of carbon dioxide noted can be explained by the presence of ethane in proportions of a trace to 4 parts of C_2H_6 to 100 parts of CH_4. Other higher paraffins may be present in small quantities, but the computations are made on the basis of ethane alone, as $C_3H_8+CH_4=2C_2H_6$. So far as the tests have been carried, the bituminous coal has yielded more ethane than the anthracite (one sample only). In fact, in several tests the explosion of anthracite gas, instead of indicating higher paraffins, suggested the presence of a small amount of hydrogen.

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[a] The Cretaceous coal from New Mexico, however, behaved differently (giving 30 to 40 per cent carbon dioxide and only 4 per cent methane), but that is outside the field of this report.

Carbon dioxide was found to be a more variable constituent of the gas, depending on the nature of the coal from which it came. The various experiments with the Monongah coal show that in most of the samples it amounted to 1 to 3 per cent of the gas which accumulated in the bottles. In the bituminous coal from the Mansfield mine at Carnegie, Pa., carbonic anhydride became much more important, reaching 13 per cent of the total gas given off. But on the other hand, careful analyses made over mercury failed to detect any carbon dioxide in two out of the four portions of gas from the anthracite coal of Nanticoke, while the analyses of the other two portions revealed the presence of only small quantities of this gas. Although the proportion of methane steadily increased as the experiment progressed, in general the proportion of carbon dioxide fluctuated during the period of observation.

The volume of nitrogen in the bottles fell rapidly during the progress of these experiments. Apparently much of the nitrogen which was obtained from coal by this and other methods, especially that portion of the gas which came off most readily, is not to be regarded as gas held by the coal while in the undisturbed strata, but as nitrogen absorbed by the coal after it became exposed to the air in the mining operations. Some of it was derived from air adhering to the coal and tubes in spite of the effort of the mercury pump to remove it. The leakage of air into the bottles could take place only while they were out of the water jar and connected with the pump. Hence, most of whatever inleaking air there may have been was quickly pumped over into the gas receiver with the rest of the gas, and was determined in the analysis on the basis of the amount of oxygen found. Only such air as could leak into the bottle, between the closing of the screw clamp and the immersion of the bottle in the water jar after sealing the rubber-tube connection with glass plug and paraffin coating, could remain in the bottle with the coal during the interval between tests. Absorption of oxygen from such air by the coal would leave an excess of nitrogen in the gas. But as less than one minute elapsed between the closing of the screw clamp and the immersion of the bottle, the amount of leakage was reduced to a small figure. The excess of nitrogen in the analyses of the portions of gas taken at the end of the half-year period indicated that the coal did contain nitrogen as a truly original gas. This may have come originally in part from air buried with the accumulated vegetable matter and in part from the decomposition of nitrogenous compounds in the organic matter whose metamorphism produced the coal.

The minor constituents of the gas from coal were carbon monoxide and one or more members of the olefin series, most probably ethylene.

The above figures represent the character of the gas escaping from lumps of coal averaging somewhat less than a cubic inch in size. The evolution of gas had in no case ceased at the end of the six-months period. Instead, gas was still steadily accumulating in the bottles, though at a diminishing rate. The composition of the last portion of the gas which would eventually escape, if the experiment were carried on for a much longer period, can only be inferred from these experiments with the lump coal. However, from the studies on the finely crushed coal, from which the gas escaped much more rapidly and completely in a given length of time than from the coarser fragments used in the above tests, more can be learned on this question. Two representative experiments with coal crushed in the rock crusher so as to pass through a 10-mesh sieve, and then bottled in a vacuum, may be selected to illustrate the composition of the gas which came from the coal after the main bulk of the free gas had been liberated and the outflow had nearly ceased.

Analyses of gases escaping from crushed coal bottled in a vacuum, with relation to the coal by volume.[a]

EXPERIMENT E.[b]

Gas.	First 6 weeks.		Next 10 weeks.		Next 10 weeks.	
	Percentage.	Relative volume.	Percentage.	Relative volume.	Percentage.	Relative volume.
Carbon dioxide	2.00	0.019	0.82	0.002	15.27	0.018
Carbon monoxide	.20	.002	.16	....	2.86	.004
Olefins	.29	.003	.27	.001	.55	.001
Paraffins	55.99	.542	64.31	.169	47.31	.058
Air: Oxygen	.18	.008	8.56	.022	2.70	.019
Air: Nitrogen	.68		25.88	.068	12.91	
Nitrogen (excess)	40.66	.393	....	....	18.40	.022
	100.00	.967	100.00	.262	100.00	.122

[a] The first analysis in each of these tables was made by the usual technical method of Hempel; the last two analyses in each case were made over mercury with the apparatus described by Bone.

[b] Coal from the face of fourth right entry off F face heading, Monongah mine No. 6, crushed and passed through a 10-mesh sieve. The rate of evolution of methane is shown by curve 2 of fig. 1.

EXPERIMENT F.[a]

Gas.	First 2 weeks.		Next 10 weeks.		Next 14 weeks.	
	Percentage.	Relative volume.	Percentage.	Relative volume.	Percentage.	Relative volume.
Carbon dioxide	2.28	0.019	4.35	0.011	20.77	0.034
Carbon monoxide Olefins	.79	.007	1.54	.004	13.35	.022
Paraffins	62.57	.535	30.51	.076	41.77	.069
Air: Oxygen	.12	.005	[b] 12.38	.148	.15	....
Air: Nitrogen	.45		[b] 46.85		.57	....
Nitrogen (excess)	33.79	.290	4.37	.011	23.39	.038
	100.00	.856	100.00	.250	100.00	.163

[a] Coal from the face of H manway in Monongah mine No. 6, crushed so as to pass through a 10-mesh sieve, and then quickly placed in the vacuum bottle. The rate of methane liberation is shown by curve 7 of fig. 1.

[b] While the gas was being pumped out a leak unfortunately appeared in the tubing connecting the vacuum bottle with the exhaust pump.

According to the foregoing table the relative proportion of both carbon dioxide and carbon monoxide increased greatly during the last weeks of each experiment, chiefly in consequence of the rapid slackening in the output of methane. This gas, because it diffuses and transpires at more rapid rates than the other gases mentioned, escaped from the coal sooner than the less active molecules, and hence the stored-up supply of free methane in the coal was more quickly depleted than that of carbon dioxide. Thus, on theoretical grounds, the coal may be expected to give off carbon dioxide for a longer period than methane. But these tables not only indicate an increase in the relative proportion of carbon dioxide and carbon monoxide during the latter part of the experiment, but they appear to show also an absolute increase in the volume of the oxides of carbon evolved per unit of time. During the first few weeks after the coal was bottled in a vacuum there was a reduction in the rate of outflow of all the gases, but during the last ten weeks of the half-year period the evolution of the oxides of carbon apparently proceeded at an accelerated rate. This feature was most conspicuous in experiments E and F, but the same phenomenon was also shown, though in a less striking manner, in the results of the two other similar series of analyses which furnished the data for curves 4 and 8 of figure 1.

The experiments with the rock crusher indicate that a large part of the free gas held by coal is mechanically imprisoned, under pressure, within the pores, interstices, and lines of fracture of the coal. Such gas is released immediately when the coal is pulverized and many of the gas-holding cavities are broken open. Many of the pores charged with gas are not opened by the crushing process, so that much cavity gas still remains in the crushed coal. Of the gas exhaled when the coal is placed in a vacuum, it seems safe to assign the bulk of the methane, carbon dioxide, and other gases which escape from the coal, rapidly at first, but at a progressively declining rate, to this mode of occurrence. The gases under pressure in the interstices of the coal are supposed to reach the surface by diffusion, or more strictly, transpiration, and to escape until in time the gas thus mechanically held has bled itself out. The curves showing the rate of escape of methane support this view in regard to that gas. But the behavior of carbon dioxide and carbon monoxide in this respect appears to be different. The declining volumes of these gases during the first few weeks are natural enough, as the cavity gas comes off in greatest volume immediately after the coal is crushed. But reasons for the apparently increasing volumes toward the end of the experiments are less easily found. Possibly the increment of carbon dioxide and carbon monoxide may come from a state of occlusion. Charcoal, which is like coal, is known to absorb the oxides of carbon in much greater volume than hydrogen[a] and probably also in greater volume than methane, though the figures for the latter are not at hand. The presumption, therefore, is that of the coal gases the oxides of carbon are likely to be held in greatest volume as occluded gas. But why such gas, even if occluded, should be liberated most rapidly after so long an interval is not apparent at the present time. Perhaps the explanation is to be found in chemical changes. For the present, however, the cause of this phenomenon must be left open. Further experimentation, to determine how generally the rule is true of different coals, is necessary before more is made of this point.

COMPARISON WITH MINE GASES.

To make a comparison between the composition of the gas which escapes from the bottled coal in the laboratory, and that which issues from the rock strata, a few analyses of feeder gas from the mines may be introduced:

Analyses of feeder gas.

<table>
<tr><th>Number.</th><th>CO_2.</th><th>CO.</th><th>C_nH_{2n}.</th><th>CH_4.</th><th>H_2.</th><th>Air.</th><th>N_2 (excess).</th></tr>
<tr><td>1</td><td>1.45</td><td>..........</td><td>.09</td><td>50.67</td><td>..........</td><td>29.33</td><td>18.46</td></tr>
<tr><td>2</td><td>1.37</td><td>.03</td><td>..........</td><td>31.99</td><td>..........</td><td>58.32</td><td>8.29</td></tr>
<tr><td>3</td><td>2.04</td><td>..........</td><td>.20</td><td>90.42</td><td>..........</td><td>6.02</td><td>1.32</td></tr>
<tr><td>4</td><td>2.39</td><td colspan="2">.26</td><td>92.17</td><td>..........</td><td>2.63</td><td>2.55</td></tr>
<tr><td>5</td><td>1.59</td><td>.04</td><td>.49</td><td>91.31</td><td>.82</td><td>1.10</td><td>4.65</td></tr>
</table>

1. Accumulation of gas at roof 20 feet from face of swamp entry, Darr mine.
2. Gas and air from drill hole in the face of right air course of main entry, Darr mine.
3. Feeder on eighth right entry, off main southwest entry, Cardiff mine, Cardiff, Ill.
4. Feeder on main southwest entry in Cardiff mine.
5. Gas issuing under high pressure from standpipe at surface 100 yards southeast of railroad station, at Luzerne (near Wilkesbarre), Pa., from anthracite coal.

The presence of a higher member of the methane series, probably ethane, was noted in Nos. 1, 3, and 4, but the paraffins have here been computed as so much methane. In No. 5, after the removal of the hydrogen by palladium, the explosion indicated only methane.

A comparison of the foregoing table with that on page 26, after the proper allowance is made for air and nitrogen absorbed from the air by the coal used in the laboratory experiments, fails to show any significant difference between the feeder gas encountered in the mines and the gas extracted from lumps of coal in the laboratory by means of a vacuum. But a comparison with the table on page 29 shows that, while the feeder gas bears a close resemblance to the gas which is obtained from the finely crushed coal during the first few weeks under reduced pressure, it is quite different from the gas which is finally exhaled from the fine coal after it has stood some months

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[a] Moissan, Chimie minérale, vol. 2, pp. 251-253.

and has lost the bulk of its free gas. The feeder gas does not contain the high percentages of carbon dioxide and carbon monoxide which characterize the last gas to escape from the fine coal. Feeder gas therefore represents that portion of the gas which is first to escape from the coal and which comes out most readily. It would seem to be that portion of the gas which, having been mechanically held at the outset in the interstitial spaces throughout the mass of the coal stratum, has subsequently escaped from the scattered pores in the coal and has accumulated along more or less connected lines of fracture, or other places of weakness or increased porosity. Traveling along these, it now issues into the mine workings from distinct orifices, cracks, or localized portions of the coal bed, at a more rapid rate and in greater volume than it is elsewhere exhaled from the solid coal.

Necessarily the issuance of gas in the form of feeders, under pressure, must die out long before the steady exhalation from the body of the coal, though the same lines of fracture continue to serve as paths of discharge for the gases slowly but steadily gathering in the porous reservoirs back in the coal. And to judge from the slowness with which even small lumps of coal manifest a change in the character of the gas transpiring from them, even when favored by a reduction of pressure, it would seem that a very much longer period of time would be required to produce the change in composition which the behavior of the finely crushed coal suggests will ultimately occur in the gas freed from the solid coal.

But in the case of pillars and other coal surfaces long exposed to the the weathering action of the mine air, there enters another factor which is absent in the vacuum-bottle experiments—that is, the steady oxidation of the coal by the oxygen of the air. Experiments on coal bottled in air, under ordinary barometric pressure, show that oxygen is rapidly absorbed by the coal until, after a few days, there remains often only 1 or 2 per cent of oxygen in the free gas in the bottle. At the same time a certain proportion of the oxygen uniting with the coal comes off again as carbon dioxide, but this, at least during the short time of the experiment, amounts to only a small part of the oxygen entering the coal. Perhaps with an abundance of air and a much longer period of time, so as to allow the coal to absorb oxygen to its full capacity, a much larger proportion of it might eventually reappear from the saturated hydrocarbon compounds, as carbon dioxide.

The feeder gas originates back in the coal seam, away from the influence of the air, and hence it does not contain carbon dioxide from the direct oxidation of the coal. But the exposed coal surface must produce carbon dioxide in this way and thus supply the mine air with carbonic acid, which, though coming from the coal, is largely independent of the free gas content of the coal. This property appears to vary in different coals. The gassiness of a certain coal is not necessarily an index to the volume of carbon dioxide which may be developed from it as a contribution to the mine air. A few analyses made in Germany of the air from unexploded mines indicate a higher proportion of carbon dioxide, in comparison with methane, than is found in the feeder gas, suggesting that the oxidation of the coal may be a more prolific source of the carbon dioxide encountered in the mines than the outflow of the free gas stored within the coal.

RATE OF ESCAPE.

The samples of coal were kept in the vacuum bottles for twenty-six weeks, or just half a year. At stated intervals during this time the gas which had accumulated was pumped out and analyzed. As methane was by far the most abundant gas thus obtained, as well as the most important from the standpoint of this investigation, the volumes of that gas given off per unit volume of coal were taken as the standard. Curves were plotted, as in figure 1, to show the rate of escape of this gas from the coal, the ordinates of the graph representing the relative volumes of methane, and the abscissas expressing the progress of time in weeks.

Descriptions of the samples of coal and the conditions from which the several curves were plotted follow:

Curve 1. Methane from coal collected from the face of the fourth right entry, off the F face heading, in mine No. 6, at Monongah, December 13, 1907; bottled in vacuum January 23, 1908.

Curve 2. Same coal as No. 1. Crushed in vacuum on January 27 by means of coal crusher, and then placed in the vacuum bottle.

Curve 3. Methane from coal collected from room 3 on third right off second north heading, in mine No. 8, at Monongah, December 12, 1907; bottled in vacuum January 23, 1908.

Curve 4. Same coal as No. 3. Crushed in vacuum in coal crusher January 28, and then placed in the vacuum bottle. Coal passed through 30-mesh sieve.

Curve 5. Coal from the face of the east return air way in mine No. 8, Monongah. Collected December 17, 1907; bottled in vacuum February 10, 1908.

Curve 6. Coal from face of right main, Naomi mine. This is the most gassy point seen in the mine. Collected December 14, 1907; bottled February 11, 1908.

Curve 7. Coal from face of H manway, mine No. 6, Monongah. Collected December 13, 1907; crushed in vacuum March 17, 1908, and immediately placed in vacuum bottle.

Curve 8. Same coal as No. 7. Crushed in air under full barometric pressure on March 18, 1908, and immediately placed in vacuum bottle.

Curves 1, 3, 5, and 6 show the escape of methane from lumps of coal averaging approximately the size of a marble. Curves 2, 4, 7, and 8 indicate the volume of gas which escaped from coal crushed so that all of it would pass through a 10-mesh sieve, a considerable part of it being necessarily much more finely reduced than this.

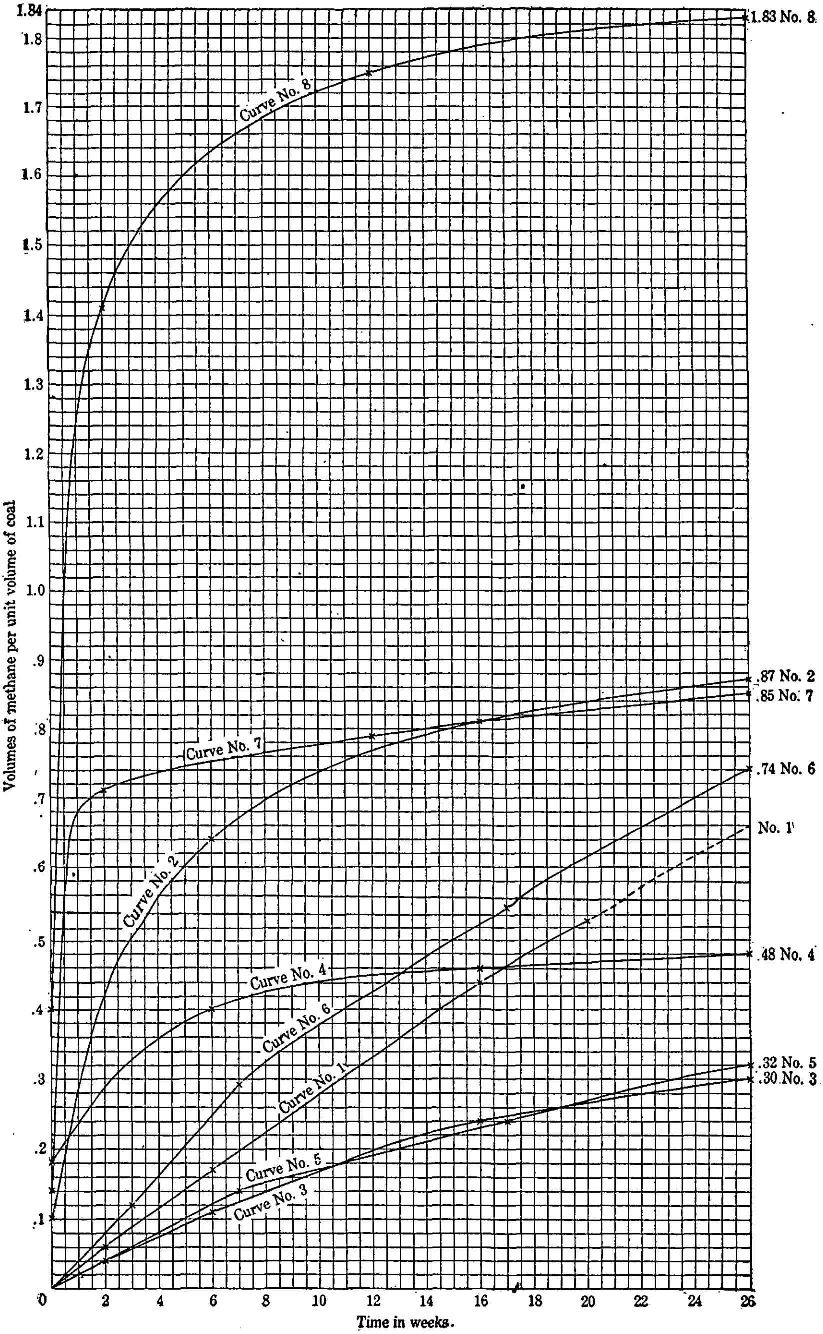

FIGURE 1.—Diagram showing rates of escape of methane from coal. (For explanation see text, p. 33.)

The volumes of methane liberated during the process of crushing are also included in these curves. Hence curves for the crushed coal instead of commencing at the zero point start at points on the vertical axis corresponding to the volume of methane lost during the process of crushing.

The four curves representing the lump coal show that the escape of methane from fragments of coal, even in a vacuum, takes place slowly and steadily and must in some cases continue for a very long period of time. Curve 1 is nearly a straight line, showing that the evolution of methane was nearly as rapid at the end of twenty weeks as when the coal was first placed in the vacuum. In the other three experiments the rate of escape declined more rapidly.

The relation between the size of the coal fragments and the rate of gas escape is strikingly shown by comparing the curves obtained from the crushed coals with those representing the same coals in lumps. Curves 1 and 2 were parallel experiments with the same coal, as were also curves 3 and 4. The finely crushed coals gave out methane at a very rapid rate for a short time after being bottled, but the rate soon rapidly declined. In the experiments represented by curves 7 and 8 the escape was exceedingly rapid during the first week after the crushing, but had greatly slackened before the end of the second week. Bottles 2 and 4 were not opened until the end of the sixth week, so that these two curves are not so sharply bent.

It is clear from these experiments that the gas escapes more readily, and at first in greater volume, from the fine coal than from the coarser lumps, but that the supply of free gas held by the fine coal is more quickly depleted, while the loss from the lump coal is more uniform. After a time, therefore, the coarse coal gives off gas more rapidly than the fine. The graph shows that the curves for the same sample of coal approach each other and will apparently come together in time, probably at a point where the gas supply of each has been practically exhausted. It seems probable, therefore, that the size of the coal, whether finely divided or in the form of coarse lumps, has little influence on the total amount of methane evolved in a sufficiently long period of time, but that it makes a very great difference in the rate at which the gas is given off. The phenomenon appears to be chiefly one involving the quantity of gas stored within the coal which can escape, and not one of gas generation during the interval of time.

Some of the results of these experiments on the rate of escape of gas from Monongah coal may be summed up in the following generalizations:

1. Reduction of pressure removes the gases from coal slowly—a matter of weeks and months.

2. Finely powdered, fresh coal gives off more methane during six months in a vacuum than the same amount of lump coal subjected to the same conditions. But presumably during a much longer period of time approximately the same volume of gas should be expected to come off from either type of coal.

3. Reduction of pressure, acting for only a few hours or even a few days, is far less effective in extracting the entrapped gas than crushing the coal, either in a vacuum or under barometric pressure.

4. Crushing coal to a certain degree of fineness yields approximately the same volume of methane whether the operation is performed in a vacuum or in an atmosphere of air or carbon dioxide.

5. Crushing the coal to the degree of fineness of which the crusher is capable removes only a minor proportion of the free gas stored within the coal. For Monongah coal already crushed, either in vacuum or under full atmospheric pressure, will yield more methane during the next two weeks in a vacuum than was liberated during the process of crushing.

PRACTICAL SIGNIFICANCE OF RATE.

The escape of methane, which takes place slowly and steadily, even from small lump coal, and at a rate that is much influenced by the size of the coal, must continue very steadily for long periods of time from the solid coal in the mines. This means that throughout every portion of a mine, in the old workings as well as the new (except in the portion of the seam near the surface from which the gas has been slowly escaping during long geologic ages), a steady outbreathing of methane gas is to be expected. This may be independent of recognizable "feeders" and "blowers" and may come from the massive coal, as well as from distinct cracks and fissures leading back to storage reservoirs. But because this gas escapes as slowly as it does steadily, it does not often become dangerous in mines where the ventilation is good; but old, abandoned workings, cut off from the rest of the mine and from the ventilation, soon fill with methane from this continual exhalation of gas.

A much greater danger lies in those more rapid outbursts of fire damp which unexpectedly flow into the new workings when a strong blower or reservoir of gas is encountered. Necessarily the quantity of gas suddenly forced into the workings must vary within extremely wide limits, depending on the nature and extent of what may, for convenience, be termed the storage reservoir. These so-called reservoirs of gas are, in reality, porous portions of the coal seam or adjacent strata, or a series of fissures, in which the gas has accumulated and is now stored, at many places under very great pressure. When a crack or fissure leading back to a region of stored gas is encountered in mining operations, an outflow of gas into the workings results. Sudden falls of rock from the roof often open avenues of escape for pent-up gas. When lines of communication with extensive reservoirs of stored gas are opened, large quantities of fire damp may flow into a portion of the mine in a short time and thus render the air in this part of the mine explosive. These lines of communication may be opened either in the ordinary mining operations or because of the formation of new lines of fracture accompanying the natural deformative movements of the strata. Settling of the overhead beds, together with a general redistribution of the strains caused by the removal of the coal, is likely to open new sets of fissures and seal old ones. Hence there may be periods of more gas and periods of less gas, depending on the local movements of the strata and the effect of such movements, by opening or closing fissures, on the facility with which the pent-up gases can find lines of egress. No appeal, however, is here made to seismic or volcanic disturbances in other parts of the world, whose influence on the local conditions must be trivial.

From these experiments it has seemed safe to conclude that the solid coal in the seam must continue to supply methane for long periods of time. This means that as the supply of gas collected in reservoirs is reduced by escape into the mine, the adjacent coal has a tendency to yield gas to replace that which is lost, until (in case the avenue of escape is cut off by movements of the strata or other causes) a state of approximate equilibrium is established between the gas distributed throughout the mass of the coal itself and that accumulating in the so-called reservoirs. If a reservoir of gas were tapped by boring and the gas removed, the reservoir would, in the course of time, be likely to become recharged, partly at least, with more gas supplied by the adjacent coal, provided the avenue of escape became closed. Just how rapidly a depleted reservoir might be resupplied with gas, and what bearing this factor has on practical mining, must be left an open question for the present.

EFFECT OF BAROMETRIC CHANGES.

When the lumps of coal were placed in the vacuum bottles and the air was exhausted by means of the mercury pump, it was found that the reduction of the pressure to a fraction of a millimeter caused the immediate escape of only a small quantity of methane. The exhaust air from the bottles of Monongah coal contained methane in volumes ranging up to 0.002 of the volume of the coal. Lumps of coal from the Naomi mine and the Mansfield mine at Carnegie, Pa., added similarly small volumes of methane to the exhaust air. Three samples of coal from the mine at Cardiff, Ill., gave only traces of methane, but a fourth, from a gassy portion of the mine, gave off 0.003 of its volume of methane. A bottle of anthracite coal from No. 1 north shaft of the Susquehanna Coal Company, at Nanticoke, Pa., gave off methane to the extent of 0.03 of the volume of the coal while the air was being pumped out of the bottle. The time required to remove the air from these bottles was about twenty minutes. Thus a sudden drop of 740 to 750 millimeters in pressure within twenty minutes does not bring out a very large volume of gas. Experiments already described have shown that time is required to bring out the gas, even in a vacuum.

To discover how much more gas is given off from coal under low pressure than under the full barometric pressure, 20 pieces of bituminous coal from the Mansfield mine at Carnegie, Pa., were placed in a vacuum bottle and the air exhausted. At the same time 21 chunks of similar size, taken from the same collecting can, were placed in a bottle filled with air. The two bottles were then submerged side by side in a water jar. At the end of ten days the gas which had accumulated in the interval was pumped out and analyzed. The coal which had been bottled in a vacuum was found to have given up 0.25 of its volume of methane, while methane amounting to 0.14 of the volume of the coal had accumulated in the bottle that had been filled with air. A similar experiment with two bottles of anthracite coal from Nanticoke, Pa., showed, after an interval of one week, exactly the same relative volume of methane in each bottle—1.07 times the volume of the coal. As in each experiment the volume of methane liberated was greater than the volume of oxygen which the coal absorbed from the air, the final pressure in the air-filled bottles was greater than the barometric pressure.

Low pressure aided the escape of gas from the bituminous coal, but it appears to have had little influence on the liberation of gas from this sample of anthracite coal. That identical volumes of methane should have escaped from the anthracite coal under such widely different pressures is perhaps to be regarded as largely a coincidence, for the distribution of gas is not uniform throughout the coal; but with about 20 fragments of the coal in each bottle, the gas content of the coal in one bottle should not differ greatly from that in the other. It is to be noted that, while the total pressure in each of these air experiments was very different from that in the parallel vacuum experiment, the partial pressure due to methane alone started at zero in each bottle and at the conclusion of the experiment with the anthracite coal had become as great in one bottle as in the other. In considering the influence of barometric fluctuations on the volume of gas exhaled by the coal in the mines, however, it is the total gas pressure which is of significance, rather than the partial pressure due to methane.

It would seem therefore that even the greatest fluctuations of the barometer, which do not exceed 40 millimeters, can not have very great influence on the volume of gas escaping from the interstices of the coal itself. But in the case of feeders and blowers, in which the gas escapes for the most part directly from accumulations stored within more or less connected systems of fissures and zones of fracture, instead of from minute pores in the coal, the effect of the diminution of pressure probably is more marked. This should be particularly true wherever the stored gas is under only a moderate pressure and the pathway of escape into the mine workings is readily followed;

the strong blowers coming from the reservoirs far back in the coal, where the gas is held under high pressure and communication with the coal surface is more difficult, are necessarily much less affected by the relatively slight barometric changes.

Heise and Herbst bring out the point that, although frequent measurements have shown that the gas stored up in the fresh, undisturbed coal often is under pressure amounting to several atmospheres, these high pressures are obtained only by boring several meters back into the coal; and that close to the coal face the gas is under a pressure but slightly in excess of the barometric pressure.[a] Blower gas, in that portion of its course which is near the orifice, is under only a slight pressure, so that an increase in the barometric pressure adds resistance to its outflow, causing it to slacken, whereas with a falling barometer the outflow of gas must become more active. In this way the common observation that the outflow of gas from blowers increases with a falling barometer and slackens perceptibly with a rising barometer is shown to be entirely consistent with the high gas pressures that have been found to exist in the undisturbed coal some distance from the exposed face.

The influence of barometric changes on the outflow of air and gas into the active workings from old abandoned entries which are not completely walled off from the rest of the mine is well known and does not fall within the scope of this discussion.

GASES OBTAINED BY HEATING COAL.

Meyer,[b] Thomas,[c] Bedson,[d] Trobridge,[e] and other investigators have extracted gases from coal with the aid of heat, by warming the coal generally up to the boiling point of water, and in some experiments as high as 200° C. In many tests the higher members of the paraffin series, such as ethane, propane, and butane, were obtained in considerable proportions. At least one gas of the olefin series was often present in notable quantities.

The present analyses of feeder gas from the mines and of the gas which slowly escaped from the coal bottled in a vacuum, as well as of that liberated directly by crushing the coal in the rock crusher, do not reveal the presence of any such high proportions of the heavier hydrocarbons. But these gases were all extracted at ordinary temperatures. As the constituents of coal include various hydrocarbon compounds, some of which may be supposed to be partly decomposed or volatilized at even moderate temperature, there comes to mind

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[a] Heise and Herbst, Bergbaukunde, vol. 1, 1908, pp. 458-461.

[b] Von Meyer, Ernst, Jour. Chem. Soc., vol. 25, 1872, pp. 798-801.

[c] Thomas, J. W., Jour. Chem. Soc., vol. 28, 1875, pp. 793-822, and vol. 30, 1876, pp. 144-152.

[d] Bedson, P. Phillips, and McConnell, W., Trans. Fed. Inst. Min. Eng., vol. 3, 1892, pp. 307-310; vol. 7, 1894, pp. 27-53.

[e] Trobridge, F. G., Jour. Soc. Chem. Ind., vol. 25, 1906, p. 1129.

the suggestion that a portion of the olefins and higher paraffin gases obtained from these European coals, instead of existing within the coal in the free state, may have been produced from chemical decomposition induced by the heat employed. To test this possibility, parallel experiments were undertaken. A can of fresh bituminous coal from the Pittsburg district being selected for this test, one portion of the coal was stored for thirty days in a vacuum bottle; a second portion was pulverized on an anvil so as to pass through a 10-mesh screen, and then quickly placed in a suitable glass tube connected with the mercury pump, and the air removed. This tube was then kept for three hours successively at 50° (water bath), 100° (boiling water), 150° (oil bath), and 200° (metal bath). The gas obtained during three hours at each temperature was collected and analyzed. The same experiment was then repeated with anthracite coal from the vicinity of Scranton, Pa. The results, expressed in volume of each gas relative to the volume of the coal as unity, are given in the following tables:

Analyses of gases obtained from coal in a vacuum at different temperatures.

BITUMINOUS COAL.[a]

Gas.	With exhaust air.	At 50°.	At 100°.	Standing over night.	At 150°.	At 200°.	Total.
Hydrocarbon vapors					0.02	0.04	0.06
Carbon dioxide	0.02	0.08	0.06	0.01	.03	.01	.21
Carbon monoxide		.01			.01		.02
Olefins		.01					.01
Ethane			.01		.02	.03	.06
Methane	.07	.58	.63	.11	.70	.17	2.26
Air: Oxygen		.17	.03		.17	.07	1.74
Nitrogen		.67			.63		
Nitrogen (excess)		.06	.14		.02	.06	.28
		1.58	.87		1.60	.38	4.64

[a] 32.56 grams of 10-mesh coal taken from the face of room 21 on No. 4 southeast butt, off No. 6 face entry, in the Mansfield mine at Carnegie, Pa.

ANTHRACITE COAL.[a]

Gas.	With exhaust air.	At 50°.	At 100°.	Standing over night.	At 150°.	At 200°.	At 300°.	Total.
Hydrocarbon vapors			0.02		0.02	0.02	0.03	0.09
Carbon dioxide	0.01	0.18	.15		.02	.02	.01	.39
Carbon monoxide		.01	.01		.01		.01	.04
Olefins		.01						.01
Ethane			.01		.01	.01		.03
Methane	.18	1.06	.99	0.20	.52	.22	.08	3.25
Air: Oxygen		.08	.01	.03	.03	.02	.02	.53
Nitrogen		.30	.04					
Nitrogen (excess)		.39	.12	.02				.53
		2.09	1.35	.25	.61	.29	.15	4.87

[a] 32.33 grams of 10-mesh anthracite coal taken from the E gangway, Babylon vein, in No. 6 colliery at Inkerman, Pa.

The other portions of these two coals were kept in vacuum bottles at low pressures for thirty days. At intervals during this period the gas which had accumulated was pumped out and analyzed, in order to furnish additional data on the rate of methane liberation (see pp. 33–36). The gas was pumped from the bottle containing the bituminous coal at the end of each ten days; from the anthracite at the end of each week, except that the fourth period was extended to nine days to complete the full thirty days.

Of the different portions of the gas analyzed, the last portion in each test furnishes the truest index to the character of the gas given off by the coal when allowed to stand under reduced pressure, as after the removal of several portions of gas the extraneous nitrogen resulting from air still adhering to the coal when bottled, has been largely removed. The gas was still coming off rapidly at the end of the thirty days.

The following table indicates the character of the last portion of the gas obtained from these two vacuum bottles:

Analyses of gases given off by coal during last 10 of 30 days in a vacuum.

Gas.	Bituminous coal.		Anthracite coal.	
	Per cent.	Relative volume.	Per cent.	Relative volume.
Carbon dioxide	12.34	0.01		
Carbon monoxide	.22			
Olefins			0.29	
Ethane	1.90			
Methane	80.64	.10	98.58	0.80
Air: Oxygen	.58		.07	
Air: Nitrogen	2.19		.26	
Nitrogen (excess)	2.13		.80	.01
	100.00	.11	100.00	.81

Ethane was present in the gas from the anthracite coal, if at all, only in small quantities. In two of the four analyses made of the gas from this coal the result of the explosion determinations indicated a small amount of hydrogen instead of higher paraffins. The explosions in the other two analyses pointed to the presence of a small proportion of ethane accompanying the methane.

A comparison of the three tables shows that for these two coals the gas extracted by heating the material up to 200° C. is somewhat, though not radically, different from that which slowly exudes from the coal when bottled for a period at ordinary temperatures. The heat caused the expulsion of such uncombined gas as was ready to escape at ordinary temperatures, and in addition developed some new gas from the nongaseous constituents of the coal. Most conspicuous among these new products were the vapors of hydrocarbons which at ordinary temperatures are normally liquids. Benzene was probably the most prominent of these vapors. The hydrocarbon vapors began to appear in notable quantities at 100° and increased in importance as the temperature was elevated. The volume of ethane also rose slowly with the increase of heat, suggesting that some of this gas did not come from a state of mechanical imprisonment in the pores of the coal, but was produced by chemical action induced by the heat. Gases of the ethylene series remained unimportant, even up to 300°, in the experiments with the anthracite coal.

The high proportions of higher hydrocarbon gases obtained by Meyer, Thomas, and Bedson by heating German and English coals up to 200° were not found in the gas from these two samples of Pennsylvania coal. By heating dust from the Darr mine up to 350°, however, both olefins and higher paraffins, which at lower temperatures had appeared only in moderate quantities, were made important constituents of the gas evolved. (See tables on pp. 57-58.) Such gases could have come only from chemical action or from a state of true occlusion, for they must inevitably have been liberated in considerable volume at the lower temperatures as well had their liberation been merely a question of escape from the interstices of the coal. Substantiating this view in a measure is the testimony afforded by the vacuum bottles. These experiments show, at least as regards the coals used in these investigations, that the gas slowly coming off from the crushed coal at the end of a period of six months at very low pressures is not notably richer in the higher members of the marsh-gas series than the gas rapidly exhaled at the beginning of the experiments. These higher hydrocarbons do not diffuse and transpire so rapidly as methane, but if they were present in any considerable volume, mechanically held within the pores of the coal, as is the methane, a period of six months would seem sufficient to permit their escape in notable proportions.

STUDIES ON COAL DUST.

EVIDENCE THAT DUST TOOK PART IN EXPLOSIONS.

The analyses of the atmosphere in the return air ways of these exploded mines were made from samples collected five to sixteen days after the explosions. The systems of ventilation were not yet in good repair and were less effective than usual. The after damp had been largely removed, as the analyses discussed under that head show. The accumulation of methane, however, because only a partial restoration of the ventilation had been effected, was probably greater, per volume of air, than was usual when the ventilating systems were in regular working order. This was certainly so in some places. Yet the analyses, most of which were collected so as to get the maximum of methane, show that the average percentage of this gas throughout the workings of each of the mines was far below the least proportion required to render the atmosphere explosive. Except in samples 17 and 18, collected on different days at the same point in the Darr mine, the analyses of air from the return air currents, away from the coal face, showed less than 1 per cent of methane. Throughout the intake air passages there should have been still less explosive gas. Methane in notable proportions was found only in very local accumulations, either at the coal face or along the roof extending for a short distance from the face. As already remarked, the gas samples, except the specimens of return air, were collected with a view to obtaining the maximum percentage of methane. The figures in the table on page 29 may therefore be taken as expressing the most gaseous conditions which could be found, even locally, in the mines.

Only very local explosions near the coal face could result from such accumulations of fire damp, if this fire damp were the sole explosive agent. In the Monongah mines it was only at a few selected spots that a gas cap could be detected in a Wolf lamp. The main return air currents contained less than half of 1 per cent of methane. Under the conditions of ordinary atmospheric pressure a mixture of air and gas containing less than 5.5 per cent of methane is rarely explosive. In view of this fact it is difficult to see how a general explosion, completely traversing both the Monongah mines, could be possible from gas alone. Compression resulting from a local gas explosion may be supposed to render explosive adjoining air containing somewhat less than 5.5 per cent of methane, but this explanation does not seem adequate.

The other agent present in these mines in large quantities which may, under the proper conditions, become explosive was the coal dust. On entering these wrecked mines after the explosions this potentially explosive material was everywhere to be seen. A thick coating of fine coal dust was found to have settled upon practically everything on which it could lodge throughout the mines. Because of this coating the normally shiny coal of the ribs and faces had become of a uniform dull-black color. In the Darr mine in particular the dull-black dust-covered ribs of the entries in the exploded portion of the mine afforded a striking contrast to the clean, shiny coal in the portion of the workings to which the explosion had not penetrated, possibly owing to the increasing wetness of the entries in that direction. An enormous quantity of coal dust stirred up by an explosion, however originating, is thought, because of the large volumes of inflammable gas which can be rapidly distilled from it at temperatures above 300° C., to have added fuel to the explosion and to have played a very important part in the propagation and extension of the flame throughout the entries where there was little fire damp.

CHARACTER OF DUST DEPOSITS.

The dust deposits observed in the exploded sections of these mines were of several kinds. First, there was the nearly universal coating of dust which had settled upon ribs, timbers, and pavements, inby and outby sides alike, and which was clearly the result of the quiet settling of the floating dust after the disturbing force of the explosion had passed. As this dust settled upon the coal after the explosion, and hence independently of the direction of the blast, it throws no light on the course which the explosion took.

Dust accumulations of another type were those deposited during the passage of the explosion and to a certain extent determined by the force of the blast. Their location thus afforded valuable evidence as to the direction in which the explosion traveled. They were of two sorts, which may be designated "uncharred dust" and "charred dust."

The uncharred dust consisted of a mixture of coal dust, fine slack coal, and finely divided shale, which had been driven into protected corners and plastered against timbers, props, and other obstructions by the advancing explosion. These deposits were most frequently observed on the exposures facing the oncoming explosion, but here and there they were found on both the stoss and lee sides of an obstruction. On some of the exposures facing the explosion the dust was found to have aggregated in the form of a sharp arête, or ridgelike deposit, to each side of which the air blast must have been deflected. Many deposits of this variety of dust approached an inch in thickness. On the other hand, they graded almost imperceptibly into the universal coating of after-explosion dust described above, which they closely resembled in general constitution.

"Charred dust" has been found a convenient term to apply to those deposits of dust which have been partly coked or charred by the heat of the explosion. They differ essentially from the uncharred dust in having lost, by distillation, a portion of their volatile hydrocarbons and in having become coked while in the heated plastic condition. At some points in the mines, where the distillation appeared to have progressed further than usual, there were to be seen on the surface of the charred dust tiny lustrous, silver-like globules, which represented the highest degree of coking observed in the mines. In general, the deposits of charred dust were found as isolated patches in sheltered nooks in the lee of projecting ledges of coal where the force of the explosion was least felt. However, many of the ribs, particularly in room necks or within the rooms, were extensively plastered with charred dust. In several such places in the Darr mine slabs of charred dust a foot square and half an inch or more in thickness could be peeled from the coal rib.

Although the presence of charred dust in various parts of an exploded mine is important as showing the presence of the explosion flame in those parts, the exact location and position of the dust are of much greater significance, as they indicate the direction in which the flame traveled. According to the researches of Sir William Galloway,[a] conducted with the aid of a gallery in which mixtures of fire damp, air, and coal dust were exploded, the "crusts of coked dust were found on the shelves farthest removed from the explosion chamber." Observations in exploded mines made by various authorities have generally agreed that the deposits of charred dust are located chiefly on exposures facing away from the source of the explosion. The distribution of the charred dust in the Monongah and Darr mines was, for the most part, in accord with this view. However, there were many exceptions to this rule. These were most conspicuous at points where the relatively slight mechanical effects of the explosion suggested that the force of the blast was reduced. The deposits of coked dust which faced the source of the explosion were generally small, scattered patches, which had the appearance of having been plastered into cracks directly by the on-coming flame rather than deposited by eddying currents in the lee of projecting ledges.

DUST SAMPLES.

A splendid opportunity to make a comparative study of charred and uncharred dusts was afforded by the conditions in room 3 on No. 3 right entry off No. 2 north heading, in mine No. 8 at Monongah. In this room the deposits of both varieties of dust were unusually heavy, particularly upon the props. The outby sides of these timbers (facing the entry) were thickly covered with dust which showed no indication of charring or other visible evidence of having passed through an explosion. The inby sides of the same props were completely plastered with well-charred dust. The opposite sides of these timbers presented a very striking contrast. Specimens of these different dusts, which were so admirably separated by the mechanics of the explosion, were collected by spreading a piece of canvas on the ground and then scraping down the dust, first from one side and then from the other. The charred dust from the inby exposures fell in cakes, while the dry, uncharred dust showed the general consistency of flour. At the same time that separate coal-collecting cans were filled with charred and uncharred dust from props about 45 feet from the mouth of the room, a third can was filled with fresh coal dug from the rib at a point about 30 feet from the room mouth.

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[a] Proc. Roy. Soc. London, vol. 33, 1882, pp. 437-445, 490-495.

Analysis of this material gave the following figures:

Analyses of dust samples, compared with fresh coal from same locality.[a]

	Moisture.	Volatile matter.	Fixed carbon.	Ash.
Fresh coal from rib	1.24	35.28	59.88	3.60
Uncharred dust, 1	2.30	24.13	45.01	28.56
Uncharred dust, 2	2.34	23.43	45.19	29.04
Charred dust, 1	1.13	24.78	58.11	15.98
Charred dust, 2	1.20	24.36	59.33	15.11

[a] The method of analysis was the official method recommended by the coal-analysis committee of the American Chemical Society, except for the determination of volatile matter, where the modified method, described in Bull. U. S. Geol. Survey No. 323, pp. 36-39, was substituted.

The two analyses of each of the dusts are not duplicate analyses of the average dust, obtained by the usual quartering process, but were made from distinct samples taken from opposite ends of the cans, in order to show how much variation there might be in the composition of each dust. But some mixing of the flourlike, uncharred dust must have taken place during the transportation of the can from the mine to the laboratory.

The most striking feature of these comparative analyses is the high proportion of ash in the dusts compared to that in the original coal. This high ash was due to an admixture of shale, numerous small particles of which were recognizable in the ash residue after the fixed carbon had been burnt out of the dusts. This shale had been derived from the strata of the roof and floor, partly through the force of the explosion and partly from the previous mining operations. The uncharred dust contained nearly twice as much ash (shale) as the charred dust. This is significant, for if the two dusts contained the same proportion of admixed shale when the flame reached them the loss of a considerable portion of the volatile hydrocarbon matter from the coked dust would correspondingly raise the percentage of ash and shale in that dust. Hence, without some conflicting agency, the charred dust should be characterized by a higher percentage of ash than the corresponding uncharred dust.

EXPLANATIONS OF DUST EFFECTS.

Mine timbers, heavily plastered on one side with charred and coked dust containing 15 per cent of ash and shale, while the opposite faces were covered with a thick deposit of uncharred dust carrying nearly 30 per cent of mineral waste, may well give a valuable clue to some vital factor in the explosion. The explosive process resulted in two very striking differences in dusts deposited only a few inches apart, but in different situations. If we seek the relation between the charring action of the flame and the percentage of shale, it is clear that the difference in the proportion of shale and ash can not be the result of the coking process, for this process can only increase the difference. The reverse alternative, that the difference in charring has come as a direct result of the difference in the shale content of the two dusts, seems more promising. It is a well-recognized fact that the presence of a noncombustible substance, intimately mixed in any considerable proportion with combustible matter, renders that matter less inflammable than it is in the pure state; and that if sufficient noncombustible matter is added the mixture will become incapable of sustaining combustion by itself. It may be that this principle has been operative here. The explosion flame was able to burn with sufficient vigor to coke the dust with which only 15 per cent of shale was mixed, but where the shale impurity amounted to 28 to 30 per cent of the total, the flame seems to have failed to reach the intensity necessary to coke the dust.

The explanation of the difference in the quantity of fine shale on the opposite sides of the timbers is perhaps to be found in the marked difference in the specific gravity of the coal and the shale. The sample of coal from this room had a specific gravity of 1.273. No specimen of this Monongah shale was collected, but an average shale of this sort would have a specific gravity of about 2.6, or twice that of the coal. So great a difference should have a marked influence on the facility with which such dusts are transported by air blasts, and also on the conditions under which they will be deposited.

In room 3 on third right entry off the second north heading the uncharred dust, characterized by the high shale content, was on the outby sides of the props, while the coked dust with less shale impurity, coated the inby surface of these props. The explosion did not originate in this room, but advanced into it from the entry, and hence its blast was directed against the outby facing exposures. The storm of coal and shale dust being driven against the outby sides of the props, portions of both dusts lodged there; but it is probable that there was collected on these exposures a relatively larger proportion of the shale, which, owing to its greater density, was driven straighter and with more force against the props, while relatively more of the lighter coal dust was swept around the props by the eddying currents. As the blast passed around each prop and an eddying current was formed in the lee of the prop, the lighter coal-dust particles would be most easily deflected from their previous courses and most abundantly plastered on the lee side by the eddy, while the heavier particles of shale, because of their greater momentum, would tend to continue in less deflected lines beyond the influence of the prop. It follows that on the inby or lee side of the timbers there would be proportionately more coal dust and proportionately less shale dust than on the outby exposures.

An alternative though not radically different hypothesis to account for the deposition of the purer coal dust on the inby faces may be entertained. In this no appeal is made to eddying currents sweeping around the timbers and sifting out and depositing relatively more of the coal dust than of the shale dust on the lee sides. The storm of dust is supposed to have continued past the timbers to the face of the room, where the force of the blast was cushioned and many of the heavier particles of shale were dropped. The weaker return wave produced by the reaction might then bring back a relatively larger proportion of the lighter coal dust, which would be deposited directly against the inby exposure of the timbers.

The high proportion of shale in the dust which was being driven against the outby sides of the props, by diluting the combustible coal dust and at the same time absorbing much of the heat produced by the flame, without itself contributing fuel to the explosion, may have had such a damping effect on the flame that the dust was not charred. But in the lee of each prop, where, in the eddying current, the proportion of shale had become much reduced, the flame was able to burn with greater vigor, and the dust became partly coked. Or, if we follow the alternative hypothesis, the coking process took place while the coal dust, purified by leaving much of the shale near the face of the room, was being carried back to the props by the weaker return wave. This view possesses certain possible advantages over the other, in that more time is allowed for the coking of the purified coal dust while traveling back from the coal face, and also because with it may be postulated great compression as the blast drove against the coal face, attended by sudden liberation of heat, which in turn facilitated the coking of the suspended coal dust returning toward the props.

CAUSE AND MANNER OF COKING.

The question naturally arises, to what extent may the coking of the dust be due to the charring effect of the flame after the dust has been deposited, and to what extent was the dust already coked when it was plastered against the obstacles where it lodged. This includes the allied question whether typical charred dust can be formed by a return flame, or sweep of hot gases, coming back along the path of the explosive blast and coking a deposit of the dust which, up to that time, had not been charred. To determine the coking effect of a flame upon aggregated coal dust, fresh coal from the face of room 1 on No. 33 heading, Naomi mine, was finely powdered and a dome-shaped pile of it, half an inch in height, subjected to the full flame of a Bunsen burner for thirty seconds. A thin, fragile disk of charred dust, less than an eighth of an inch in thickness, was the result. This small disk, about the size of a dime, was so poorly consolidated that it could scarcely be handled without falling to pieces. Below this thin covering the dust was not visibly affected by the heat of the flame.

In the mines, on the other hand, charred dust was found in favorable places in layers an inch in thickness and so tenacious that slabs a foot square could be stripped off. Such slabs usually showed rather uniform coking throughout, and uncharred dust was not found beneath the cakes.

This uniformity of coking naturally favors the conclusion that the dust was coked while in the air and deposited in the semiplastic condition. The force of impact, which may be supposed to have packed the dust, may account for the greater tenacity with which it holds together. These conclusions are greatly strengthened by the laboratory experiment, which shows that a Bunsen flame, impinging upon fresh coal dust for thirty seconds, produces only a superficial layer of char, much less consolidated than the charred dust in the mines. The dust in the mines could have been exposed to the flame and hot gases for only a fraction of this length of time, as the small splinters of wood on the mine timbers generally were not charred, though locally evidence of some burning was found. Hence the coking of the typical charred dust had probably already taken place, for the most part, before it was deposited.

LOSS OF VOLATILE MATTER.

The coking process consists chiefly in the distillation and expulsion of a portion of the volatile hydrocarbons, which add fuel to the flame. In order to obtain an idea of how much volatile matter was lost in the explosion we may take the comparative figures for these dusts, whose true import is obscured by the admixture of so much shale, and reduce them to a common, shale-free basis. Assuming that the original coal containing 3.60 per cent of ash, and reducing the ash content of both dusts to this proportion, we obtain the figures below:

Analyses of dust samples recalculated on basis of equal proportion of ash.

	Moisture.	Volatile matter.	Fixed carbon.	Ash.
Fresh coal	1.24	35.28	59.88	3.60
Uncharred dust, 1	3.09	32.57	60.74	3.60
Uncharred dust, 2	3.18	31.83	61.39	3.60
Charred dust, 1	1.29	28.43	66.68	3.60
Charred dust, 2	1.35	27.67	67.38	3.60

The figures for the charred dusts calculated in this way are not strictly correct, as no account is taken of the fact that, because of the loss of a portion of the volatile matter, the percentage of ash, instead of remaining at 3.60, should be increased proportionally, but the difference is not great and causes no error of importance.

The two analyses of uncharred dust show a loss of 2.71 and 3.45 per cent of volatile matter, compared with the fresh coal. A portion of this difference is thought to be due to the fact that the material used in the analysis of the fresh coal was passed through a 10-mesh sieve, but was too coarse to pass through a 30-mesh sieve, whereas the uncharred dust was much finer than this. N. W. Lord[a] has brought out the fact that, with the modified method of analysis, the determination of volatile matter will appear about 1 per cent lower for very finely powdered coal (80-mesh and finer) than for coarser coal (20 to 40 mesh). Allowance is to be made for this difference, and a later determination made with very finely powdered material gave 33.44 per cent of volatile matter in this sample of coal. Strangely, the loss of volatile matter has been approximately compensated by a gain in the moisture, perhaps due to the shale, so that the percentage of fixed carbon has not been greatly changed.

Compared with the original analysis of the fresh coal, the analyses of the charred dust indicate a loss of 6.85 and 7.61 per cent of volatile matter and but little change in the moisture content. The charred dust, according to these figures, has lost more than twice as much volatile matter as the uncharred. But as the variability of the moisture content has some influence on these figures, it may be well to give the ratios between the fixed carbon and the volatile matter. This ratio for the fresh coal is 1.69 to 1; for the uncharred dust, 1.86 and 1.93 to 1; and for the charred dust, 2.34 and 2.44 to 1. Although it is possible that a small amount of fixed carbon has been consumed, along with the volatile combustible hydrocarbons which the charred dust has fed to the explosion flame, this would seem relatively unimportant, for experiments show that, although coal dust when heated to redness yields up its volatile matter readily and rapidly, considerable time is required to burn out the fixed carbon that remains after the escape of these more volatile products. Thus, when only a part of the volatile matter has been removed from the dust samples obtained in the mines, it is not likely that much of the so-called fixed carbon has been consumed, at least from these particular samples.

Analyses of the gas evolved from coal dust at temperatures up to 450° C. show that these combustible products comprise the vapor of benzene and associated hydrocarbons, ethylene and its homologues, methane and the higher paraffins, and carbon monoxide, together with a little hydrogen sulphide. (See tables on pp. 57–58.) At the same time certain noninflammable gases, such as nitrogen, carbon dioxide, and sulphur dioxide, are produced in more or less subordinate proportions. The combustible gases are evolved in large volumes and some of the molecules of the higher hydrocarbons, be-

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[a] Experimental work conducted in the chemical laboratory of the fuel-testing plant at St. Louis: Bul. U. S. Geol. Survey No. 323, 1907, p. 40.

cause of their complexity, require large proportions of oxygen. It is therefore to be expected that, in many cases, these inflammable compounds will not find sufficient oxygen for their complete combustion. The need of more oxygen is doubtless one of the reasons why dust explosions seek the fresh intake air in preference to the less oxygenated return currents. At Monongah mine No. 8 the destruction at the pit mouth was very great.

COMPARISON OF OTHER DUST SAMPLES.

These samples of charred and uncharred dust from a room in Monongah mine No. 8, which were so admirably separated by the explosion itself, were the best samples available to furnish data on the mechanics of the explosion. Other cans were filled with dust from the Naomi and Darr mines, but conflicting factors, whose possible influence can not be determined, make results based on some of them of uncertain value. Analyses of other samples of charred dust do not all reveal the low proportion of shale observed in the dust on the props in room 3 just described. They are given below:

Analyses of additional dust samples.

No.	Material analyzed.	Moisture.	Volatile matter.	Fixed carbon.	Ash.
1	Charred dust	0.88	16.24	45.38	37.50
2	Do	1.25	14.54	52.79	31.42
3	Do	1.14	13.33	70.78	14.75
4	Uncharred dust	6.07	19.51	45.81	28.61
5	Do	2.31	20.46	31.68	45.55
6	Do	1.24	20.84	28.78	49.14

1. Charred dust collected on December 14, 1907, inside the screen (9 meshes of 1 inch each) of the electric headlight on a motor, center main at No. 28 chute, Naomi mine. The headlight of the motor faced the explosion and the dust was driven straight through the screen against the reflector. The high percentage of shale was perhaps a momentum effect.

2. Charred dust collected on January 5, 1908, from the inby end and inby bumpers of a mine car, 25 feet outby No. 1 left butt, on entry 28, in the Darr mine. At the point where this sample was obtained there was some suggestion of a conflict of forces, so that the value of the analysis is uncertain. The car from which this dust was obtained was the last (inby) of a trip of 12 cars. It had been derailed and partly turned sidewise, but those who examined the car differed as to the direction of the force which derailed it. In the ash which resulted from burning this charred dust in a crucible, numerous fragments of shale as large as a cubic millimeter were noticeable. These fragments of shale were both more numerous and larger than those in the ash from the charred dust on the props in the room in mine No. 8 at

Monongah. To determine whether a portion of the shale might have been swept into the already charred mass by a return blast of hot gases coming down the entry, the outer portion of a cake of this dust was cut off and an ash determination was made of the protected portion of the cake. The result was 29.72 per cent of ash in the protected half of the cake, compared with 31.42 per cent ash for the whole.

3. Charred dust collected January 4 from the face of room 1, on No. 8 left butt, off the swamp entry, in the Darr mine. This specimen represented a very extensive and thick deposit plastered against the coal face. As it was at the end of the room, this dust was necessarily blown directly against the face upon which it lodged. Evidence of more than a very moderate mechanical force was lacking at this point, and this was true generally where deposits of charred dust occurred in similar situations facing the source of the explosion. With less force, the explosion wave could gather up and carry along less of the heavier shale. This sample of charred dust contained the lowest percentage of shale impurity, and was at the same time the most thoroughly coked of all the dusts collected.

4. Uncharred dust gathered January 2, from the inby end of an 8-inch pipe 18 feet in length, which was lying along the left rib of the main entry, just opposite entry 21, Darr mine. This dust, which had accumulated in the pipe, contained a much lower proportion of shale than the dust on the floor near by, showing that the coal dust was more easily swept into the pipe than the heavier shale. At the same time, the dust in the pipe was in a position unfavorable to participation in the explosion.

5. Uncharred dust collected January 2 from the pavement along the left rib of the main entry, just opposite entry 21, in the Darr mine. This was 15 feet outby from the iron pipe from which sample 4 was obtained.

6. Uncharred dust from the other end of the can from which sample 5 was taken. This analysis was undertaken to show the amount of variation in the composition of this dust.

RESTRAINING FACTORS—SHALE AND DAMPNESS.

The three samples of uncharred dust were obtained near the point in the Darr mine where the last bit of charred dust was found. Between this point and the mine mouth, a distance of about a mile, no charred dust was seen. Though the explosion continued past this place, the flame left no record of itself, and the work done by the mechanical forces is less and less distinct. Whether the restraining influence of so high a proportion of noncombustible shale, or the reduction of the explosive capacity of the dust by the loss of a portion of its inflammable gas and the partial oxidation incident to its long exposure to the air, or entirely different conditions, have been the most potent factors in damping the explosion in this main entry must for the present remain largely a matter of conjecture.

In the first two samples of charred dust analyzed, the ash residue was characterized by fragments of shale considerably larger than any found in the dust from the props in the room at Monongah. This is a factor of much importance, for the possible damping effect of a certain proportion of shale is dependent, to a great extent, on its fineness of division. If the total mass of the shale is concentrated in a few large pieces this noncombustible matter can have little influence on an explosion; but the same weight of shale in a finely divided state, and intimately mixed with the coal dust, may have a marked restraining influence on an explosion, and if in sufficient quantity render the coal dust incapable of propagating an explosion.

The chief result of the presence of shale dust is the absorption of so much heat from the flame that the latter can not perpetuate itself. Essentially the same principle underlies the experimental observation of German investigators that, when the walls of an explosion gallery are sprinkled with water, dry dust may be stirred into the air without being set off by the usual charge of dynamite used to explode the particular variety of dust. After a large number of trials with charges of 25 to 300 grams of gelatin dynamite, the most explosive mixtures of fettkohlen dust in a dry condition remained unignited when the walls of the galleries were sprinkled just before the trials. With the gallery walls dry, a charge of 50 to 75 grams of dynamite sufficed to explode this dust.[a] The investigators stated their belief that the effect of such sprinkling was due less to the water rendering the dust nonexplosive, than to restraint of the genesis and propagation of the coal-dust explosions as a result of the rapid cooling of the flame by the wet walls of the gallery.

The effect of the dampness of the walls and floor in limiting the spread of a dust explosion was indicated on entry 21 in the Darr mine. This entry led to an older and lower part of the mine, near the river level, where the workings were continually wet. The explosion, advancing along entry 21 from the main entry, carried a piece of the overcast (located 50 feet from the mouth of the entry) a distance of 220 feet and spread a deposit of fine dust on the ribs to a distance of 600 feet from the main entry. Beyond this point the coal on the ribs of entry 21 was clean and lustrous, and the rib corners and exposed edges were all very angular, in striking contrast to the partly rounded edges which had been polished by the dust blast throughout the exploded portion of the mine. As far as the coating of dust extended along this entry water lay under foot only here and there in pools, but the ribs showed increasing dampness. Farther

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[a] Niederrheinisch-Westfälischen Steinkohlenbergbaues, vol. 7, pp. 509-510.

on they became distinctly wet and standing water was abundant. No charred dust was found in this entry. Apparently the explosion flame, which had become enfeebled by the time it reached the mouth of entry 21, as previously mentioned, was completely checked on reaching the wet portion of that entry.

PRACTICAL CONSIDERATIONS AS TO DANGER OF EXPLOSIONS.

INFLUENCE OF SEASONAL CHANGE.

One of the chief lessons learned from the series of disastrous explosions in the bituminous coal mines in December, 1907, was the influence of the first touch of cold weather on the danger of coal-dust explosions. During the summer the air in the mines is cooler, on the average, than the outside air. As a consequence, when the warm air is drawn into the mine, saturated or nearly saturated with moisture, and then cooled, a certain amount of this moisture is condensed and serves to keep the mine damp. But with the approach of cold weather the conditions are reversed. The outdoor temperature becomes much lower than that in the mines. The result is that, whether the cold air going into the mines is saturated with moisture or not, as soon as its temperature rises in passing through the mine its capacity to absorb moisture becomes proportionately increased and it begins to dry out the mine. If the air is only partly saturated when it enters the mine its drying effect will be just so much greater. On January 4 and 5 tests made with a psychrometer by W. O. Snelling, of the United States Geological Survey, showed that the air was entering the Darr mine in a partly saturated condition at 25° to 35° F., but that after the air had passed through long stretches of entry and reached the coal face its temperature had risen to 60° F. and it had absorbed moisture till it contained 95 to 97 per cent of its full capacity at that temperature. This indicated the absorption of much moisture during the passage of the air through the entries. These entries, except No. 21, which led to a lower portion of the mine near the river level, and scattered pools of water elsewhere, were quite dry at the time of the inspection.

Inasmuch as the large volume of air forced through the mines keeps the dust in a dry condition during the winter except for a short time after sprinkling, the danger from dust explosions is greatest during the cold season. The disastrous explosion in the Marianna mine (Pennsylvania), November 28, 1908, and the four terrific explosions in the Naomi, Monongah, Darr, and Yolande (Alabama) mines, all of them coming in December, suggests that the period of greatest danger probably comes early in winter, when, as a result of the change in atmospheric conditions, the mines first become dry. A rapid current of air will dry a mine quicker and more completely than a slow one. Hence, in so far as dust explosion is favored by dryness of the dust, if sprinkling is the only precautionary measure used, the danger of dust explosion is increased by increase in ventilation. Up to a certain point, the more perfect the ventilation of a mine during the winter, the drier and more dangerous does the dust become. But good ventilation is indispensable to proper mining conditions, and hence any suggestion of means for reducing the dangers incident to strong ventilation without lessening the volume of air passing through the workings should be welcome, even if it only serves to stimulate further investigation.

EFFECT OF SHALE DUST ON EXPLOSIONS.

To this end the suggestions drawn from the foregoing observations in the mines and in the laboratory will be briefly stated, subject to modifications as further investigations and practical experience require. The observations and analyses give rise to a very definite suggestion as to a possible mode of reducing the liability of dusts to explode. This suggestion grows out of the striking difference which the analyses disclose between the charred, the uncharred, and the fresh coal dusts, with regard to the respective percentages of shale in them, particularly as shown on the opposite sides of the props in the Monongah mine. These differences indicate that the proportion of shale present in the dust exerted a marked influence on the degree of coking and the extent to which the dusts participated in the explosions. They suggest that the principle which seems to be involved might be applied to effectually reduce the danger of a general explosion throughout a mine, if not to render one practically impossible.

Among the possible advantages which may be claimed for the use of shale, earth, or lime mixed with water are the adhesiveness of mud and its property of holding together even after it has become completely dry. By adhering to the fine particles of coal, it would form a dust much less readily stirred into the air in every-day mining operations. A coating of mud, clay, shale, or whitewash on the ribs and props must bind the coal-dust particles to the coal or timbers with sufficient tenacity to prevent this dust from being swept up by the ordinary currents of air passing through the entries. Because of greater adhesiveness mud or soft clayey shale is preferable to the more indurated slates, but whitewash has some properties which make it superior to either.

The property of noncombustible shale to diminish the inflammability of the coal dust is not dependent on the presence of a continuous supply of moisture in the mines. Sprinkling with water alone is effective for a time; but if the dust is once made comparatively harmless by the admixture of a large amount of very fine shale or similar adhesive mineral matter it remains so (even though the mine be completely dried out) until an additional amount of coal dust has accumulated or the dusts in some way become partly separated.

Whether shale dust on the entry floors alone is competent to check a dust explosion once under way when fine coal dust unmixed with shale or whitewash is present upon the ribs and timbers can be told only by experiment. That an enormous amount of dust and coal in fine particles is swept along the entries during an explosion was clearly brought out by an inspection of the coal ribs in the exploded mines. Very generally throughout these mines, except where the mechanical force of the explosion was greatly reduced, the exposed corners and protuberances of the coal were rounded or even highly polished on exposures facing the source of the explosion, but nearly all the corresponding exposures facing away from the blast were angular and dull. This rounding indicated much abrasion and wear and resembled somewhat the familiar polishing of bowlders and pebbles by the sand blasts in arid regions. As this smoothing of corners and burnishing of exposed surfaces was all accomplished in the very short time which the explosion occupied in traveling through a given section of an entry, the mass of dust and particles of coal carried along by the blast must have been very great. If the floor of an entry should be thickly covered with fine noncombustible shale dust, it is possible that an explosion sweeping up such a mass of material might be checked by that influence alone.

COMPARATIVE INFLAMMABILITY OF OLD AND FRESH COAL DUSTS.

SUPPOSED DANGER IN OLD DUST.

The statement has been made occasionally in mining literature, but apparently without very definite experimental basis, that the old dust along the main haulage ways, which has been long exposed to the action of the air, is more dangerous than the fresh dust close to the working faces. The reason for this belief, it has been stated, lies in the presence of oxygen occluded by the dust during its extended exposure to the air. The presence of a considerable amount of oxygen condensed upon the surface and in the pores of the dust would seem to be favorable to the rapid combustion of the coal dust when the exciting cause of the explosion appears. And as it has long been known that coal absorbs oxygen from the air, it was natural to conclude that weathered coal dust which has absorbed much oxygen must be more inflammable than dust from the same coal which has been exposed but a short time.

TESTS ON DIFFERENTLY EXPOSED SAMPLES.

To throw light on several phases of this question at once, two samples of dust, placed in a vertically held combustion tube connected with the mercury exhaust pump, were heated by slow degrees up to 450° C., and the gas evolved at different stages was pumped off and analyzed. The first of these samples was old, weathered, but unexploded dust gathered from the main haulage way of the Darr mine; the second was a fine powder freshly prepared in the laboratory by pulverizing coal from the same mine. This fresh powder was placed as quickly as possible in the tube, and the air exhausted. In each experiment the exhaust air was collected and analyzed; then the tube was warmed and kept immersed in boiling water for a couple of hours, and the gas evolved was removed for analysis. After that the tube was heated on a metal bath successively to 225°, 350°, and 450° C. and kept at each temperature for several hours, and for each such period a portion of gas was obtained.

By this treatment, it was thought, could be determined not only the relative volume of combustible and noncombustible gas which the two different dusts can produce when heated up to 450°, but also the volume of oxygen which had been occluded by the dusts. At the same time, as the old dust came from an exploded mine, though unexploded itself and taken from a locality where the explosion flame had left very little evidence of its presence, it was thought best to treat, in addition, a sample of old dust which it was certain had never been at all affected by an explosion. For this purpose coal from the Darr mine was reduced to a fine powder in a mortar, spread out thinly upon sheets of paper in a laboratory hood which was not in use, and allowed to remain thus exposed to the air for a period of two months. It was then subjected to exactly the same treatment as the other two dusts.

The results of these three series of tests, expressed in volume of each gas relative to the volume of the dust, are given in the following tables:

Analyses of gases obtained from coal dust of different degrees of exposure.

[Relation to volume of dust as 1.]

OLD DUST LONG EXPOSED TO THE AIR.[a]

Gas.	Exhaust.	3 hours at 100° C.	2½ hours at 225° C.	5 hours at 350° C.	5 hours at 450° C.	Total up to 350° C.
Sulphur dioxide Hydrogen sulphide	....	....	0.01	0.09	0.02	0.10
Carbon dioxide	0.02	0.02	.18	.71	.35	.93
Carbon monoxide	.01	.004	.03	.23	.23	.27
Hydrocarbon vapors	....	....	....	....	.50	....
Heavy hydrocarbons	....	....	....	.10	.31	.10
Methane series	.006	.002	.02	.25	1.71	.28
Air (oxygen and nitrogen)	....	.03	.04	....	.02	....
Nitrogen, excess over air	....	.06	....	....	....	....
	.036	.12	.28	1.38	3.14	....

[a] Fine dust from the left rib of the main entry, just opposite entry 21, in the Darr mine.

Analyses of gases obtained from coal dust of different degrees of exposure—Continued.

FRESH DUST.[a]

Gas.	Exhaust.	2 hours at 100° C.	2½ hours at 225° C.	5 hours at 350° C.	1½ hours at 450° C.	Total up to 350° C.
Hydrogen sulphide	....	....	....	0.02	0.27	0.02
Carbon dioxide	0.01	0.03	0.04	.28	.56	.36
Carbon monoxide	....	....	.02	.06	.25	.08
Hydrocarbon vapors	....	....	....	.56	.57	.56
Heavy hydrocarbons	....	.01	.01	.19	1.05	.21
Methane series	.10	.92	.23	1.12	7.19	2.37
Air (oxygen and nitrogen)	....	.10	.01	.01	.11	....
Nitrogen, excess over air	....	....	.02	....	....	....
	.11	1.16	.33	2.24	10.00	....

[a] Coal from face of ninth left, off entry 27, Darr mine, very finely pulverized in a mortar and quickly placed in the tube and the air exhausted.

DUST TWO MONTHS OLD.[a]

Gas.	Exhaust.	3 hours at 100° C.	2½ hours at 250° C.	5 hours at 350° C.	4 hours at 450° C.	Total up to 350° C.
Sulphur dioxide Hydrogen sulphide	....	....	....	....	0.19	....
Carbon dioxide	0.02	0.02	0.16	0.59	.85	0.79
Carbon monoxide	....	....	.05	.20	.40	.25
Hydrocarbon vapors	....	....	.11	.17	1.51	.28
Heavy hydrocarbons	....	.002	.01	.06		.07
Methane series	.03	.008	.06	.35	4.86	.45
Air. Oxygen	....	.01	.02	.01	.04	....
Nitrogen	....	.04		.04	.15	....
Nitrogen, excess over air	....	.02	....	....	....	....
	.05	.10	.41	1.42	8.00	....

[a] Coal from the Darr mine, finely pulverized and exposed to the air in the laboratory.

When the fresh dust, in the experiment just tabulated, was heated to 450° C., gas came off so rapidly and was obviously so much the result of chemical decomposition and distillation of the volatile nongaseous hydrocarbons that the experiment was stopped at the end of one and a half hours, though gas was still coming off steadily. In the experiment with the dust which had been exposed for two months, the operation was stopped at the end of four hours, though gas was still coming off. As at 450° chemical action is strong, and as the temperature was not kept so uniformly at the mark as with the lower temperatures, comparative results are less significant and less trustworthy. Therefore in the total volume for each gas given in the table, only the gas obtained up to 350° has been included.

SIGNIFICANCE OF TESTS.

These three tests gave quite different results, and the variation appears to be highly significant. The old dust and, to a somewhat lesser degree, the dust exposed to the air for two months had lost a large proportion of their free methane and heavy hydrocarbons. Much of this loss was probably due to simple escape from the finely divided coal, as the experiments with bottled coal have shown that gas is continually escaping from coal and that the escape proceeds at an especially rapid rate, for a short time after pulverization, from fine coal. (See p. 35.) This escape was a distinct loss of the most available explosive constituents. On the other hand, the old, exposed dusts yielded much more of the oxides of carbon and sulphur than the fresh dust. This indicates that simultaneously with the loss of the hydrocarbon gases a process of oxidation had been going on, which had converted a portion of the carbon of the coal into carbon monoxide and carbon dioxide and some of the sulphur into sulphur dioxide. The increase in the volume of carbon dioxide and of carbon monoxide was about the same; and this showed that, while there had been some complete oxidation to the dioxide, there had also occurred some partial oxidation of the coal to compounds readily decomposed by heat with the evolution of carbon monoxide.

Sulphur dioxide was especially noticeable in the gas obtained at 225° and 350° C. from the old, weathered mine dust, though it was not prominent in the gas from the dust exposed in the laboratory. It had probably been derived from the oxidation of the pyrite in the coal to ferrous sulphate or basic ferric sulphate, which was decomposed by the heat employed, with the formation of sulphur dioxide:

$$2FeSO_4 = Fe_2O_3 + SO_2 + SO_3.$$
$$Fe_2S_2O_9 = Fe_2O_3 + 2SO_3.$$

The sulphur trioxide was reduced to the dioxide by oxygen-absorbing compounds in the coal. The dry air of the laboratory evidently was not so favorable to the weathering of the pyrite as the conditions in the mine, for the artificially weathered coal dust yielded more hydrogen sulphide than sulphur dioxide. The sulphur gas from the fresh coal was largely hydrogen sulphide. Where both gases were produced by the same dust, as from the old mine dust, sulphur dioxide was most conspicuous at the lower temperatures; at 450° C. the sulphur gas, even from the mine dust, was largely hydrogen sulphide.

Free oxygen formed only an insignificant portion of the gas obtained in these experiments and was regarded as most probably due to a slight leakage of air during the course of the heating process. In exhausting the air from the tubes, however, there was obtained, for two of the three samples, slightly more oxygen in proportion to the nitrogen than is found in pure air. The ratio of oxygen to nitrogen in pure air is 0.264 to 1. In the last 9.48 cubic centimeters of the exhaust from the tube containing the old dust, the ratio of oxygen to nitrogen was 0.265 to 1; in the last 58.65 cubic centimeters of the exhaust from the coal which had been exposed for two months the proportion was 0.264 to 1; and in the last 16.25 cubic centimeters of air from the freshly powdered coal, the ratio was 0.280 to 1. It is possible that there was a slight increase in the proportion of oxygen even in the two-months dust, and that this slight increase was obscured by the large volume of air collected. The total volume of oxygen in these last portions of the exhaust air, in terms of the volume of dust as 1, was, for the old dust, 0.11; for the two-months dust, 0.73; and for the fresh dust, 0.14. The excess of oxygen in the exhaust air therefore is quantitatively very insignificant. Moreover, in these tests it was greatest in the fresh dust, which was exposed to the air in all less than half an hour before the air was pumped out of the tube.

That exhaust air from a tube containing coal is slightly richer in oxygen than normal air was first noted by Trobridge,[a] whose work confirmed the observations made by Bedson and other investigators that oxygen and nitrogen, the former preferentially, are absorbed by coal when exposed to the air. That portion of the oxygen absorbed from the air, which is thus readily released from the coal with a relief of pressure, may be regarded as occluded gas held by the coal in the free state. This gas comes off largely on the simple relief of presssure. But the volume of oxygen which comes off on the reduction of pressure is quantitatively only a small fraction of that which has been absorbed. The foregoing tables, confirmed by the results of various other experiments, indicate that after a vacuum has been produced in the tube containing the dust or coal, very little more free oxygen is obtained when the tube is heated. Two hypotheses naturally present themselves. According to one, free oxygen still remains within the coal, but does not come off when heat is applied, because the heat causes it to unite chemically with the coal. The other is that after the absorbed oxygen has been removed by the reduced pressure, very little of the gas remains within the coal in the free state. Though chemical union might be supposed to take place at the higher temperatures, there appears to be much less reason to assume that the union which has not taken place at ordinary temperatures will proceed rapidly at 100° or 200° C. The second hypothesis, that the greater part of the oxygen absorbed has already entered into chemical combination at ordinary temperatures and that little uncombined oxygen remains in the coal, seems the more probable.

ABSORPTION OF OXYGEN BY COAL.

Although comparatively little free oxygen can be extracted from coal, experiments show that very large volumes of oxygen are rapidly and steadily absorbed by coal. It was knowledge of this fact that has suggested belief in the greater inflammability of the long-exposed coal dusts. But this idea is based on the assumption that much of this oxygen remains in the coal in the free state. The experiments with dust (see tables, pp. 57–58) indicate that, with exposure to the action of the air, there is a development of the oxides of carbon and

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[a] Trobridge, F. G., Jour. Soc. Chem. Ind., vol. 25, 1906, pp. 1129–1130.

sulphur within this dust, or of compounds which give off these gases at moderate temperatures. Coal bottled with air for a few days gives off a much higher proportion of carbon dioxide than if placed in a vacuum. But it does not give off as carbon dioxide, within a short time at any rate, more than a small percentage of the oxygen absorbed from the air in the bottle. Air bottled with Illinois (Cardiff mine) coal for two weeks contained, at the end of that time, only 1.05 per cent of oxygen and 1.59 per cent of carbon dioxide, together with 0.62 per cent of methane and 96.74 per cent of nitrogen. Thus only a small proportion of the oxygen which goes into coal comes out again (at least within the time covered by the experiment) as carbon dioxide. The formation of water by the oxidation of a part of the hydrogen in the coal is a natural explanation for the apparent disappearance of some of this oxygen. It may also be that some of the organic compounds have been only partly saturated and hence the oxygen absorbed is not given off at once as carbon dioxide, but comes off later when the oxidation has progressed further.

Significant evidence in this connection is afforded by some experiments pursued by Varrentrapp in 1865.[a] This investigator placed fragments of fresh coal in a flask and slowly passed air (free from CO_2) through the flask and into baryta water. This operation, performed at different temperatures and carried on for varying periods of time, indicated that the amount of carbon dioxide produced was very considerable. While proceeding slowly at the ordinary temperature, a slight increase of temperature greatly augmented the output of carbon dioxide. At 150° C., the highest temperature used, 3 cubic feet of air per day passing over the coal for six days caused the formation of 103 grams of barium carbonate, which corresponds to an oxidation of 12.5 grams of carbon. As this carbon dioxide came from 250 grams of dry coal containing 64 per cent of carbon, Varrentrapp believed that if this process had been continued at 150° for about three months, all of the carbon in the coal might possibly have passed over into carbon dioxide.

These experiments seem to indicate that the oxygen absorbed by coal largely enters into chemical combination. At first when coal is exposed to the air, oxygen is absorbed and condensed on the surface, or within the minute pores, in a manner analogous to the absorption of gases by charcoal—as free, chemically uncombined oxygen. But coal holds less gas in this state than charcoal does. The oxygen thus held then passes on into chemical union with the substance of the coal, oxidizing pyrite in the presence of moisture, saturating unsaturated hydrocarbons, and directly oxidizing hydrocarbon compounds with the formation of carbon dioxide and water. As the free oxygen enters into chemical combination, more of the gas is absorbed from the

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[a] Varrentrapp, F., Chem. Centralbl., vol. 36, 1865, pp. 953-954.

air; hence the process may progress steadily. The occluded oxygen, therefore, is only in a state of transition, which leads to chemical union with the coal.

DECREASE IN COMBUSTIBLE GASES.

Returning to the mine dusts, it would appear that the oxygen absorbed during the long exposure, instead of gradually becoming stored up as free gas ready to furnish rapid combustion whenever an exciting cause appears, has been steadily uniting chemically with the dust and reducing the amount of combustible matter present. A comparison of the results of the last group of tables expresses the changes which the more readily volatilized constituents of the dusts have undergone as a result of exposure. Expressed in volume of gas relative to the volume of dust, these figures are as follows:

Comparison of total volumes of specified gases obtained from dust samples.

[Relation to volume of dust as 1.]

Gas.	Old dust.	Dust exposed 2 months.	Freshly prepared dust.
Sulphur dioxide	0.10		
Carbon dioxide	.93	0.79	0.36
Carbon monoxide	.27	.25	.08
Heavy hydrocarbons	.10	.35	.77
Methane series	.28	.45	2.37

Grouping together the carbon monoxide, heavy hydrocarbons, and methane as inflammable gas, and the carbon dioxide and sulphur dioxide as noninflammable gas, the combined figures are as follows:

Comparison of total volumes of inflammable and noninflammable gases obtained from dust samples.

[Relation to volume of dust as 1.]

Gas.	Old dust.	Dust exposed 2 months.	Freshly prepared dust.
Inflammable gases and vapors	0.65	1.05	3.22
Noninflammable gases	1.03	.79	.36

Thus the old dust yielded nearly three times as much noncombustible gas as the fresh variety, but only one-fifth as much combustible gas. The dust exposed for two months in the laboratory took an intermediate place, showing that the escape of the methane and the oxidation of the dust have proceeded in the same manner as in the mine (except, perhaps, the weathering of the pyrites), but that the process had not advanced so far in this length of time. It seems probable that with a longer exposure to the air it would reach the same condition as the old mine dust.

These changes undergone by the dust during its exposure to the air must have considerable effect on its explosive properties. The loss of much of the free methane and some of the other hydrocarbon gases and vapors, coupled with a partial oxidation of the combustible material and an increase in the volume of noncombustible gases, must, other things being equal, reduce the explosive potentialities of the dust.

The figures of the foregoing tables represent only the gas evolved when the dusts are heated to 350° C. At 450° the same general differences exist in the gases produced, though more gas is evolved than at the lower temperature, and the proportions show some variation. Much higher temperatures than this are developed during an explosion, and hence more gas may be developed and exploded. Although perhaps the basis of comparison should be the total quantity of gas developed at a higher temperature, say 600°, it seems likely that the comparative explosiveness depends more on the relative volumes of inflammable gas that can be easily and quickly generated from the dust. The heat of the explosion can operate only for a very short interval of time, so that the readily freed volatile hydrocarbons must count most. Such gases are those represented in the foregoing tables. It is the initiation of the explosion and the facility with which it is propagated that are of the most vital importance. These would seem to be less dependent on the total volume of combustible gas that may be obtained from a given volume of dust, and that may or may not ultimately participate in the explosion, than on the ease with which the generation of combustible gas can be started and the products be fed to the growing flame. It is probably also true that at temperatures above 450° C. the freshly prepared dust will yield more combustible gas and vapors than the weathered dust, though it is likely that the difference will not be so great as at the lower temperatures. The analyses of even the well-charred dust from the exploded mines indicate that only a small proportion of the total volatile matter has been lost during the explosion.

CONCLUSION—FRESH DUST MORE DANGEROUS.

Because of these considerations, the conclusion seems natural that, unless the action of the air and the general weathering processes introduce some other factors here overlooked, the newly made coal dust at the working faces of the mine should, on a chemical basis alone, other things being equal, possess greater explosive potentialities than the old dust along the main haulage ways. One of the uncertain operative factors is the occluded oxygen, which may be supposed to facilitate an explosion of dust. But if the conclusion favored by the comparative tests made on these samples of dust is valid, the quantity of oxygen within the coal dust in the free state is not sufficient to play a very important part in an explosion. Moreover, the sample of freshly prepared dust gave off somewhat more oxygen when the tube in which it was placed was exhausted by the vacuum pump than either of the older samples. If the occlusion of oxygen from the air takes place with such rapidity, the new dust at the working faces must be essentially as predisposed to explosion, so far as occluded oxygen is concerned, as the oldest dust near the pit mouth. Hence it would seem that occluded oxygen is not a very important factor in this stage of the problem.

The physical state of the dust, however, is undoubtedly a factor of the greatest importance. Dryness and fineness of division of the dust must favor its ready inflammability, and in proportion as the dust in certain parts of a mine is drier and finer than in other sections, other things being equal, the danger of ignition from a blown-out shot or other cause must be increased. A study of the relative explosiveness of coal dusts according to their physical characteristics does not, however, constitute a part of this investigation.

Chemically the difference between fresh and old weathered dust, particularly in those respects which most vitally influence their relative explosive potentialities, as has been indicated by comparative experiments, is great. The dust which has long been exposed to the air has, compared with the freshly made dust, lost a very considerable proportion of its free methane and other readily escapable combustible hydrocarbons; has suffered the partial oxidation of a portion of its hydrocarbons,[a] and has stored up an increasing volume of the noninflammable gases, which are the products of combustion. It is probably safe to assume that the finer the dust the more rapid and complete has been this process. Therefore, unless other factors are involved which have been overlooked or whose importance has been underestimated, it would seem that, on the basis of its chemical properties, the fresh dust is likely to prove more inflammable and more predisposed to start and propagate a dust explosion, whatever the immediate precipitating cause may be, than the old dust which has long been exposed to the weathering action of the air. Entirely in accord with this conclusion is that to be drawn from the work of Professor Bedson, who found that while an electric current of 12.05 amperes would, by heating a resistance wire, ignite 1 gram of fine (100-mesh) fresh coal dust, it required a current of 14 amperes to heat the wire sufficiently to ignite a like amount of the same dust after it had been exposed to the air for about three weeks.

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[a] It is to be noted that this process of oxidation, which liberates heat, is identical with that which, when the heat can not readily escape, finally causes the ignition of the coal. But the coal dust probably does not accumulate in sufficient mass to prevent the rapid loss of the heat produced by the oxidation, and hence ordinarily its temperature probably does not become greatly raised.

SURVEY PUBLICATIONS ON FUEL TESTING AND MINE ACCIDENTS.

The following publications, except those to which a price is affixed, can be obtained free by applying to the Director, Geological Survey, Washington, D. C. The priced publications can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

Bulletin 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, in St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp. 10 cents.

Professional Paper 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. In three parts. 1,492 pp., 13 pls. $1.50.

Bulletin 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp. 20 cents.

Bulletin 323. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 1907. 49 pp. 10 cents.

Bulletin 325. A study of four hundred steaming tests, made at the fuel-testing plant, St. Louis, Mo., 1904, 1905, and 1906, by L. P. Breckenridge. 1907. 196 pp. 20 cents.

Bulletin 332. Report of the United States fuel-testing plant at St. Louis, Mo., January 1, 1906, to June 30, 1907; J. A. Holmes in charge. 1908. 299 pp.

Bulletin 333. Coal-mine accidents, a preliminary report by Clarence Hall and W. O. Snelling. 1907. 21 pp.

Bulletin 334. The burning of coal without smoke in boiler plants; a preliminary report, by D. T. Randall. 1908. 26 pp. 5 cents. (See Bull. 373.)

Bulletin 336. Washing and coking tests of coal and cupola tests of coke, by Richard Moldenke, A. W. Belden, and G. R. Delamater. 1908. 76 pp. 10 cents.

Bulletin 339. The purchase of coal under government and commercial specifications on the basis of its heating value, with analyses of coal delivered under government contracts, by D. T. Randall. 1908. 27 pp. 5 cents.

Bulletin 343. Binders for coal briquets, by J. E. Mills. 1908. 56 pp.

Bulletin 362. Mine sampling and chemical analyses of coals tested at United States fuel-testing plant, Norfolk, Va., in 1907, by J. S. Burrows. 1908. 23 pp. 5 cents.

Bulletin 363. Comparative tests of run-of-mine and briquetted coal on locomotives, including torpedo-boat tests and some foreign specifications for briquetted fuel, by W. F. M. Goss. 1908. 57 pp., 4 pls.

Bulletin 366. Tests of coal and briquets as fuel for house-heating boilers, by D. T. Randall. 1908. 44 pp., 8 pls.

Bulletin 367. Significance of drafts in steam-boiler practice, by W. T. Ray and Henry Kreisinger. 1909. 61 pp.

Bulletin 368. Washing and coking tests of coal at Denver, Colo., by A. W. Belden, G. R. Delamater, and J. W. Groves. 1909. 54 pp., 2 pls.

Bulletin 369. The prevention of mine explosions, by V. Watteyne, C. Meissner, and A. Desborough. 1908. 108 pp.

Bulletin 373. The smokeless combustion of coal in boiler plants, by D. T. Randall and H. W. Weeks. 1909.

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