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AN INVESTIGATION OF EXPLOSION-PROOF MOTORS

H. H. CLARK

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AN INVESTIGATION OF EXPLOSION-PROOF MOTORS.

By H. H. Clark.

INTRODUCTION.

DEFINITION OF TERM "EXPLOSION-PROOF."

The term "explosion-proof," as applied by the Bureau of Mines to an electric motor, refers to a motor inclosed by a casing so constructed that an explosion of a mixture of mine gas (methane) and air within the casing will not ignite a mixture of the same gas surrounding the motor. There are two classes of motors so constructed: First, a totally inclosed class built strong enough to withstand high internal pressures and so designed that the efficiency of all inclosing covers can be satisfactorily maintained; second, a class provided with relief openings or valves designed to relieve the pressure of an explosion within the motor casing and to cool any products of combustion discharged through the valves.

A satisfactory motor of the first class is much more expensive to build than an equally safe motor of the second class. For this reason, attempts to make motors explosion-proof have been confined chiefly to motors of the second class.

THEORY OF EXPLOSION-PROOF PROTECTION.

The function of explosion-proof devices for electric motors is to reduce below the ignition point of gas (methane) the temperature of any flames that may be discharged from the motor casing. The temperature reduction is effected by removing the requisite amount of heat from the flames during their passage through the devices. Various plans have been proposed and developed for thus removing heat from the products of explosion. The principle of the Davy safety lamp has been the basis of most of the protective devices designed for explosion-proof motors. The application of this principle consists in causing the discharged gases to pass over or through metallic plates or screens which by conduction remove the heat from the gases. In some types of devices the cooling effect of expansion is also utilized.

For the sake of simplicity, in this report the means used to cool incandescent gases are termed "protective devices" whether they consist of valves, layers of gauze, or metal plates.

PROCEDURE OF INVESTIGATION.

The investigation described in this bulletin was undertaken by the Bureau of Mines as one of several investigations having for their purpose the ascertaining of methods for lessening the risks attending the use of electricity in mining.

The bureau began this investigation by sending a circular letter to manufacturers of electric motors for mine service, stating that the bureau proposed to make tests of electric motors designed for operation in the presence of gas (methane) in order to determine their suitability for such service. This letter was sent to all manufacturers whom the bureau believed would be interested in the proposed tests. Five motors were submitted for test, no two being protected in exactly the same manner.

In this report the results of tests are related to the various types of protection employed which are described in detail.

DETERMINATION OF TEST CONDITIONS.

According to the definition of an explosion-proof motor, such a machine can presumably be safely operated in an atmosphere containing gas (methane) under conditions most conducive to explosion, provided that the protective devices with which the motor is equipped are in good condition and in their proper places. In conducting the investigation here reported, an effort was made to produce conditions that would probably introduce the greatest elements of danger. In the earlier tests especially, and to some extent in subsequent tests, it was not evident just what the most dangerous conditions would be. The design of some of the protective devices required the introduction of special conditions which are in this report recorded under the description of the tests of such devices. A list of conditions common to all tests follows.

CONDITIONS COMMON TO ALL TESTS.

CONSTANTS.

The constants of the investigation consisted in assuming:

(*a*) That sparking sufficient to ignite gas (see p. 11) was present in the motor casing.

(*b*) That the motor casing was completely filled with an explosive gaseous mixture.

(*c*) That the motor casing was completely surrounded with a similar mixture.

CONTROLLED VARIABLES.

The controlled variables of the investigation were:

(*a*) The ratio of gas to air in the gaseous mixtures.

(*b*) The point within the motor casing at which the mixture was ignited.

(*c*) The presence of coal dust within the motor casing.

UNCONTROLLED VARIABLE.

The variable which was observed but not controlled was:
The temperature of the gaseous mixture surrounding the motor.

TEST ASSUMPTIONS.

The reasons for assuming the constants are obvious and require no explanation nor comment. A discussion of the variables follows.

The ratio of gas (see p. 11) to air within the motor casing was varied from the value that gave maximum pressure and heat in order to determine the effect of slow-burning mixtures which produce a lower but longer sustained pressure.

The location of the point of ignition with reference to the relief openings was varied because that factor has an influence upon the pressures produced by explosions within the casing.

Coal dust was sifted into the housings of the relief openings in order to observe the influence of the dust upon the pressures developed within the motor casing, and also to determine if the presence of dust assists in the communication of heat from the interior of the motor casing to the gaseous mixture surrounding it.

No attempt was made to control the temperature of the motor or to increase it by operation under load lest the severity of the conditions would be lessened. Raising the temperature of the motor would have increased the temperature of the protective devices and decreased their capacity for cooling the products of explosion. At the same time, however, the amount of gaseous mixture which the casing could contain would have been decreased, the latter effect more than counterbalancing the former, as is shown below.

In testing motors for explosion-proof qualities the danger point is reached when the products of explosion are discharged through the protective devices at a temperature higher than 650° C.,[a] the ignition temperature of methane. It is reasonable to assume that, if the temperature of the discharged products of explosion is 650° C., the parts of the protective devices that are in immediate contact with the products of explosion must have attained a temperature of at least 300° C. In considering the conditions that exist when a motor is tested cold, let the initial temperature of both the gas and the protective devices be assumed as 25° C., the absolute initial temperature of the gaseous mixture being 273° plus 25°, or 298° C. The range of temperature through which the protective devices must be raised before they can discharge dangerously hot gases will therefore be at least 300° C. minus 25° C., or 275° C. If the motor be tested under the conditions of its maximum guaranteed temperature rise of 75° C. above 25° C., the aver-

[a] Dixon, H. B., and Coward, H. F., The ignition temperature of gases. Chemical News, vol. 99, 1909, p. 139.

age temperature of the gaseous mixture within the motor casing could be hardly less than 75° C. (348° C., absolute), and the temperature of the protective devices could be hardly greater than 60° C. The temperature range of the protective devices would therefore be 300° minus 60°, or 240° C., about 12.7 per cent less than when testing the motor cold. The amount of gaseous mixture that the motor casing can contain at an absolute temperature of 348° C. is $\frac{298}{348}$ of the amount that it can contain at an absolute temperature of 298° C., or about 14.4 per cent less. Thus it is evident that although the temperature rise of the protective devices necessary to produce dangerous conditions would be decreased 12.7 per cent by raising the initial temperature of the motor 75° C., the available heat in the gaseous mixture would, at the same time, be decreased by an even greater percentage.

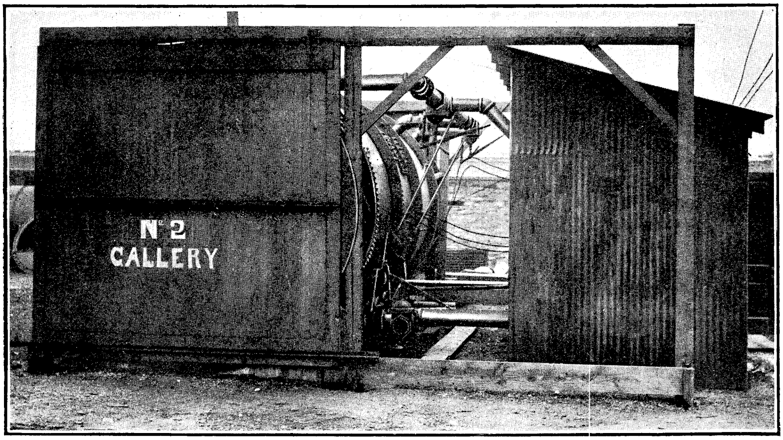
For the reasons given above, no attempt was made to raise the temperature of either the motor or the surrounding air when that temperature fell below the probable underground temperature. The pressures obtained in the tests seemed to prove the wisdom of this practice, although they do not correspond exactly in all cases. Of 17 groups of tests, made upon 3 different types of protection under conditions that allowed the effect of temperature to be satisfactorily observed, only 1 group showed a higher pressure for the maximum temperature than for the minimum, and the difference was only one-half pound in that group. In making the comparison only those groups were considered in which the mixture contained 8.6 per cent gas, and in which the tests differed in temperature by 8° C., or more.

Some of the more notable examples of the inverse variation of pressure with temperature are tabulated below. These are all abstracted from the results of tests of the type A[a] devices, the temperature variation being greater during the tests of these devices than with the other types tested.

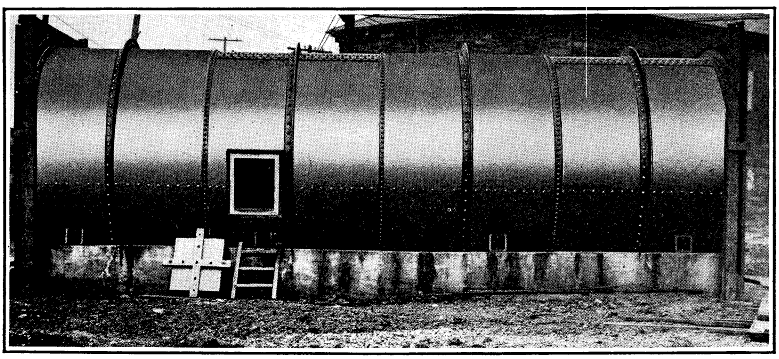
Variation of pressures with temperatures in explosion-proof motors.

Group No.	Maximum temperatures.	Corresponding pressures.	Minimum temperatures.	Corresponding pressures.
	° C.	*Pounds per square inch.*	*° C.*	*Pounds per square inch.*
1	35	19.0	6	23.0
19	24	38.0	2	43.0
34	30	35.5	3	37.5
35	23	42.0	5	45.5
17	27	20.5	0	27.5
18	18	40.5	0	45.8
31	27	36.0	3	47.0
32	15	40.0	2	47.0

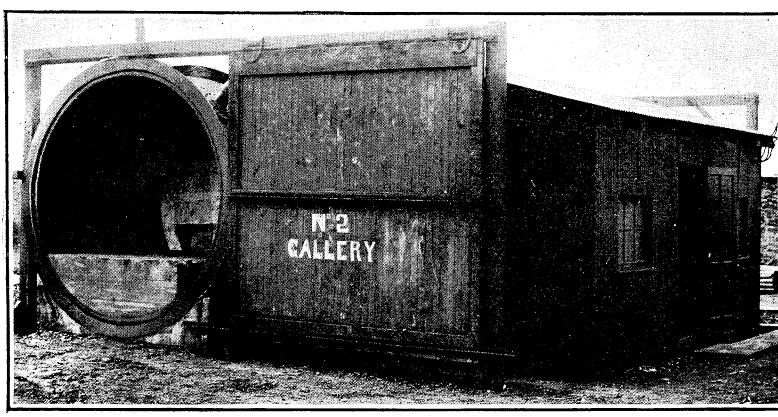
[a] See p. 23.



A. GALLERY, SHOWING TESTING HOUSE AND PIPE CONNECTIONS.



B. SIDE VIEW OF GALLERY, SHOWING MANHOLES.



C. END VIEW OF GALLERY, SHOWING PAPER DIAPHRAGM.

GAS AND EQUIPMENT USED.

GAS.

The natural gas supplied to the city of Pittsburgh was used in all tests. Its composition[a] is approximately 82 per cent methane or marsh gas, 16.4 per cent ethane, 1.5 per cent nitrogen, and a trace of carbon dioxide. The term "gas" wherever used in this report refers to this natural gas.

The most explosive mixture[b] of such gas and air is one combined in the proportion of 8.6 : 91.4. This mixture also burns most rapidly and evolves the greatest amount of heat.

In this report a mixture containing more than 8.6 per cent of gas is termed an "overgassed" mixture, and a mixture containing less than 8.6 per cent of gas is termed an "undergassed" mixture.

TESTING APPARATUS.

The apparatus used in the tests included the following:

(1) A gas-tight gallery or inclosure in which the motor to be tested was installed. (Pl. I.)

(2) A circulating fan for mixing the gas and air within the gallery.

(3) A system of piping connecting the gallery and circulating fan.

(4) A device for determining the percentage of gas in the mixture. (Pl. II and fig. 1.)

(5) A pressure indicator attached to the motor casing to record the pressure developed therein by the explosion.

(6) Spark plugs mounted within the motor casing and operated by an induction coil.

(7) A system of piping and valves connecting the motor casing with the fan intake for the purpose of filling the motor casing with the gaseous mixture.

TESTING GALLERY.

The gallery in which the motor was installed for the tests was a boiler-plate cylinder, 10 feet in diameter and 30 feet in length, set horizontally upon a concrete foundation. Seven feet from each end the cylinder was stopped off with diaphragms of heavy manila paper reinforced with cheese cloth and painted with one coat of white lead and oil to make them gas-tight. A manhole cut in the side of the gallery between the diaphragms made entrance possible without the disturbing of the paper stoppings. Observation windows of heavy plate glass were placed at intervals along the sides of the gallery. Plate I shows the general appearance of the gallery and testing house. Electrical connections were brought through bushings in the side of the gallery to a slate terminal board.

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[a] Burrell, G. A., The natural gas used at Pittsburgh: Bull. 15, Bureau of Mines, 1912, p. 66.
[b] Idem, p. 77.

Pipe connections for the circulating fan were made so that the mixtures entered and left at the same end of the gallery. The discharge point was about in the middle of one end and directed the gases horizontally along the gallery. The velocity with which the mixtures entered carried them the entire length of the gallery and in returning to the point where the fan intake was connected they filled the gallery completely with a uniform mixture.

CIRCULATING FAN AND PIPING.

A 6-inch exhaust fan, driven by an electric motor, was installed outside the gallery for mixing and circulating the gas and air. This fan, as connected, had a capacity of about 1,000 cubic feet per minute. The gas-feed connection was made to the fan intake so as to obtain a preliminary mixing of the gas and air before they entered the gallery.

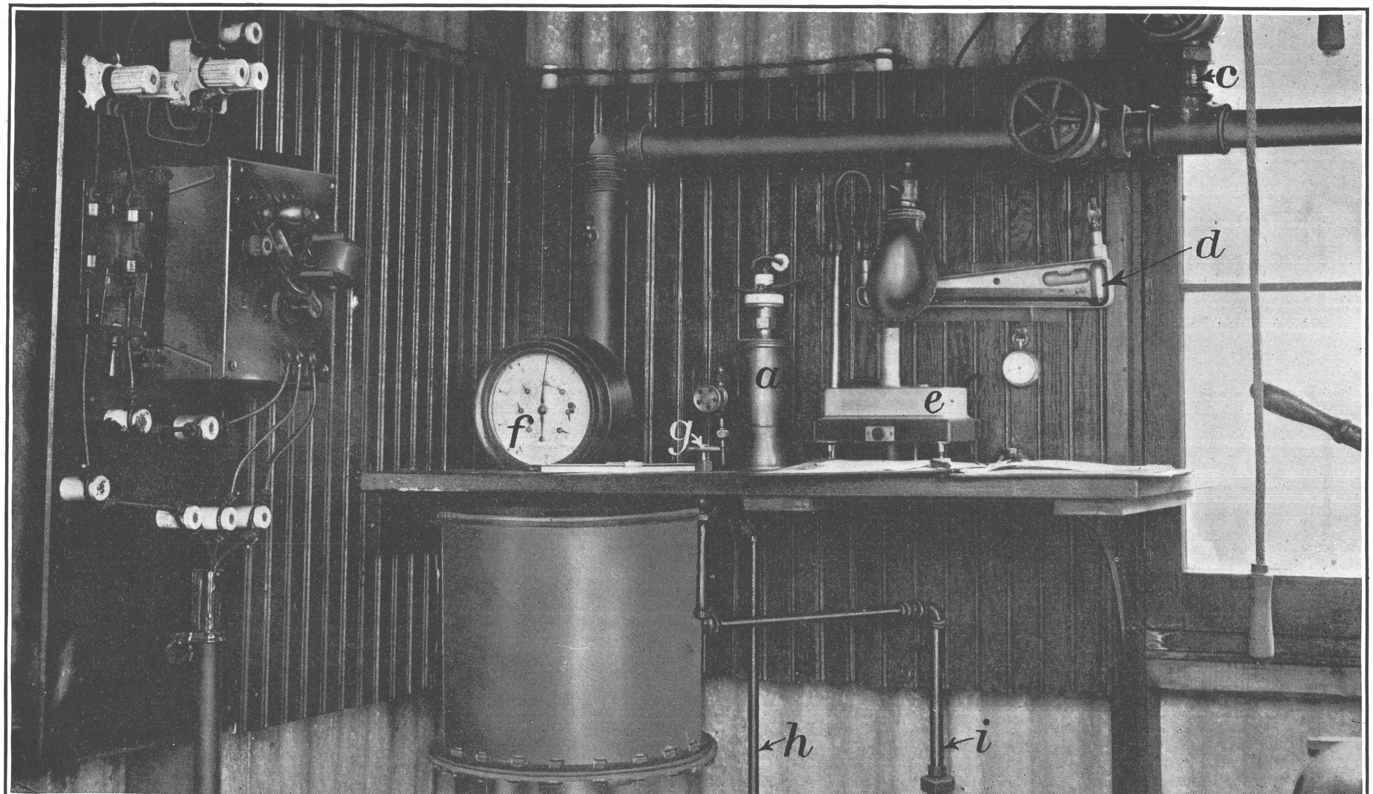
The fan was so connected to the gallery that it could be used either to circulate the mixture through the gallery, draw the mixture through the motor casing, withdraw the mixture from the gallery, or force fresh air into the gallery.

GAS-PERCENTAGE INDICATOR.

It was necessary to be able to determine quickly and accurately when the gas and air were mixed in proper proportions. Chemical analysis, although accurate, was obviously not suited to the purpose. On account of conditions which were unavoidably associated with the test it was not expedient to attempt to obtain accurate mixtures by combining proportionate volumes of gas and air. To overcome these difficulties, an instrument[a] was devised that burned a small quantity of the gaseous mixture in close proximity to a thermocouple that was connected to a delicate millivoltmeter. Plate II shows the general arrangement of the apparatus; figure 1 shows the details. This device was connected to the fan discharge so as to indicate the percentage of gas in the mixture that was being circulated through the gallery. By setting the valves in the piping system so that the fan took the mixture from the motor casing only, it was possible to determine immediately and accurately when the casing had become filled with the correct mixture.

The operation of the device was simple. The mixture was fed to the device at constant pressure, maintained by reference to a sensitive water gage connected at the point *c*, and was burned at the point *a* just below the thermocouple, ignition being accomplished by a jump spark between the point *b* and the casing of the plug. Once

[a] In this instrument use was made of a combined automobile spark plug and thermocouple invented and developed by N. Munroe Hopkins, of Washington, D. C.



ARRANGEMENT OF RECORDING APPARATUS. *a*, GAS-PERCENTAGE INDICATOR; *c*, AIR SUPPLY; *d*, WATER GAGE; *e*, MILLIVOLTMETER; *f*, GAS METER; *g*, INDICATOR-CONTROL VALVE; *h*, WATER-JACKET SUPPLY PIPE; *i*, INDICATOR CONNECTION TO FAN DISCHARGE.

ignited, the gas burned as a continuous flame and not as a series of explosions. Obviously the deflection of the millivoltmeter was maximum when the ratio of gas to air in the mixture was such that the greatest amount of heat was evolved when the mixture was burned.

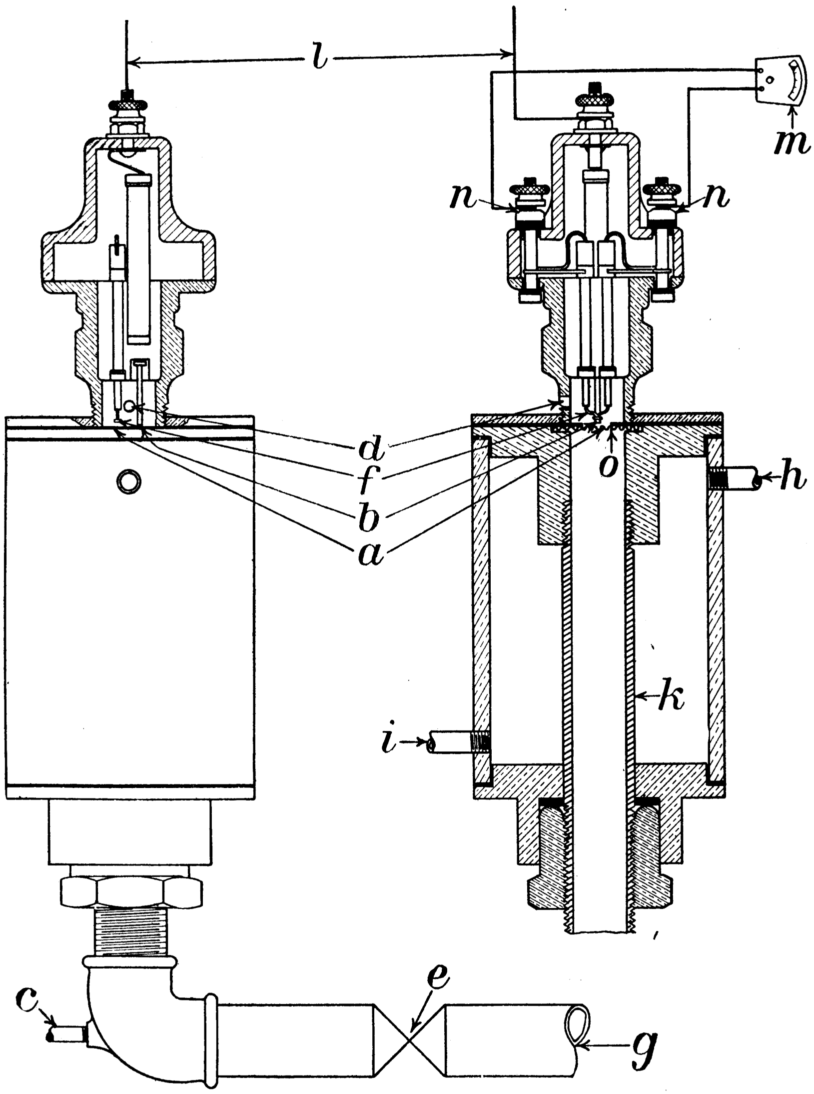


FIGURE 1.—Details of gas-percentage indicator. *a*, Point at which gas is burned; *b*, spark point; *c*, water-gage connection; *d*, vent for burned gas; *e*, control valve; *f*, thermocouple; *g*, gas intake; *h*, water-jacket discharge; *i*, water-jacket inlet; *k*, uptake tube; *l*, ignition wire; *m*, millivoltmeter; *n*, thermocouple terminal; *o*, double layer of gauze.

For the natural gas used this ratio is 8.6 per cent gas to 91.4 per cent air, and, as previously stated, this mixture is most sensitive to ignition.

The device was standardized by analysis of the mixtures that gave maximum voltmeter deflections. The results agreed closely with the theoretical value of 8.6 per cent gas. The standardizing was done in the chemical laboratory of the Bureau of Mines experiment station at Pittsburgh by G. A. Burrell, assistant chemist.

In making tests with percentages of gas greater or less than 8.6 the amount of gas required to give 8.6 per cent under the conditions of the test was first determined and then a proportional amount was used for the desired percentage. The results obtained by means of the device have been satisfactory and consistent, as is shown by the agreement of the pressures obtained in the tests. (See table, p. 10.)

RECORDING PRESSURE INDICATOR.

An indicator of the type used in taking cards on gas engines was connected to the motor casing near the relief valves. The indicator drum was wound against its spring and held in tension by a ratchet which was released by an electromagnet at the same time that the exploding spark was applied. By this arrangement a curve was obtained which resembled one-half of an indicator diagram taken on an engine. The curves are to be read from right to left; that is, the explosion is to be considered as beginning at the right-hand side of each diagram. This card showed the relative rate of propagation of the explosion as well as the maximum pressure developed within the motor casing. The maximum-pressure indication served as an excellent check upon the performance of the gas-percentage indicator.

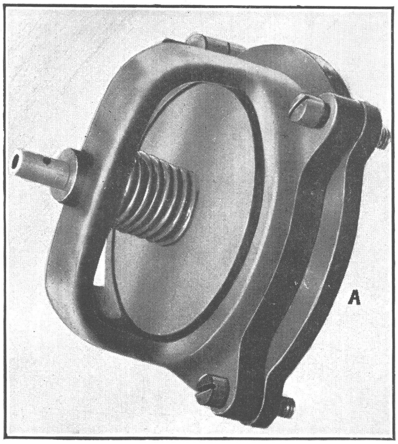
A gas-engine indicator, on account of the inertia of its moving parts, is not well suited to the observation of explosion pressures that vary rapidly over wide ranges. Although the results obtained gave all the information that was necessary for the purpose of the present investigation, it is doubtful whether the curves indicate the true variations of pressure, especially for the alternate positive and negative values recorded.

It was not considered necessary to perfect the drum-revolving mechanism so as to produce a uniform speed of rotation. The information that might have been obtained would have been interesting but was not indispensable to the investigation. Therefore the angular velocity of the drum was not made uniform and the time of rotation was not the same in all tests. The relative times of operation of the igniting spark and the drum release were also varied in order to obtain a more or less open curve at the point of maximum pressure.

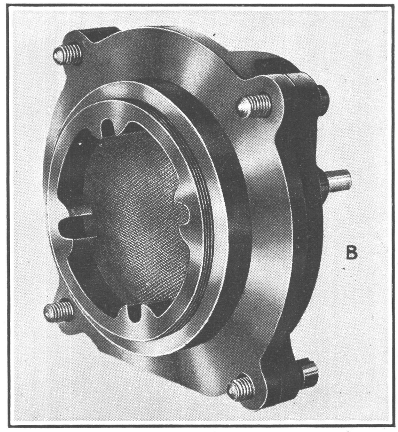
MEANS OF IGNITION.

The gaseous mixtures inside the motor casing were ignited sometimes by a spark from the brushes and sometimes by a gas-engine spark plug.

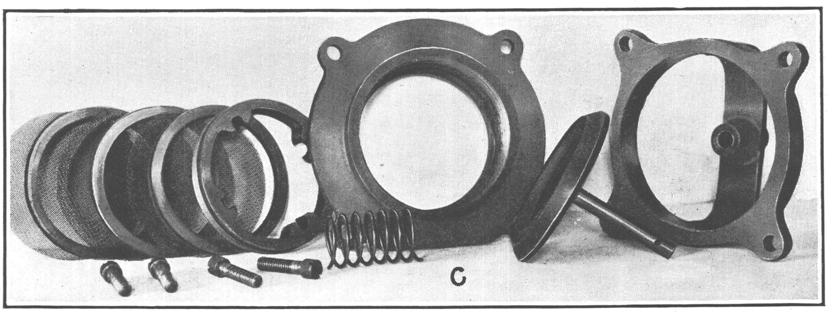
The latter method gave better control and, as comparative tests showed no difference in results obtained, was the means of ignition used in nearly all tests.



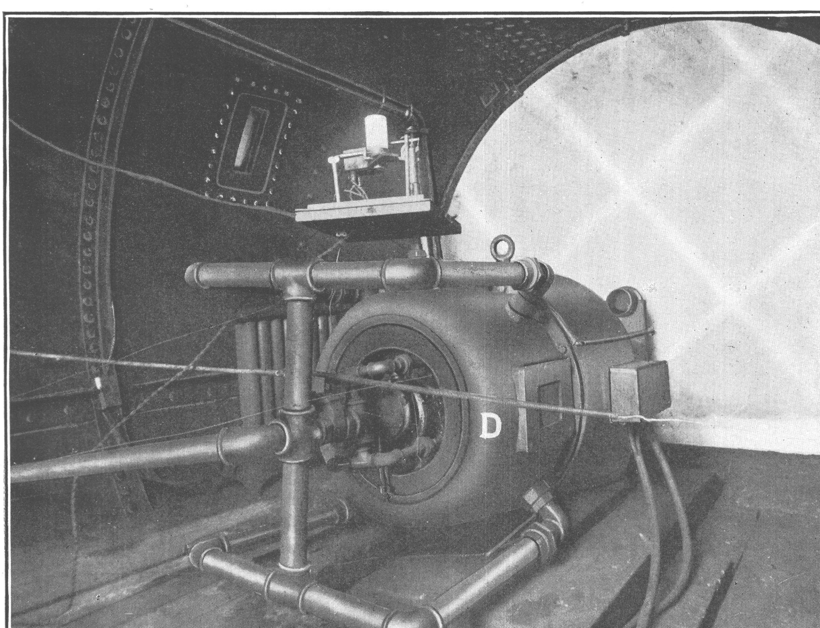
A. POPPET VALVE OF TYPE A PROTECTIVE DEVICE.



B. WIRE GAUZE OF TYPE A PROTECTIVE DEVICE.



C. MEMBERS OF TYPE A PROTECTIVE DEVICE.



D. MOTOR EQUIPPED WITH TYPE D PROTECTIVE DEVICE.

Several spark plugs were screwed into the motor casings at different points in order to determine the effect of initiating the explosion at points somewhat remote from the openings of the protective devices.

MOTOR PIPING.

In the earlier tests the pressures developed within the motor casing under presumably constant conditions varied in an annoying manner. The cause, which was not located for several months, proved to be the incomplete filling of the motor casing with the gaseous mixture. In the earlier tests only two openings in the motor casing were provided for the entrance of the gaseous mixture, and the pipe connecting the casing of the motor to the intake of the

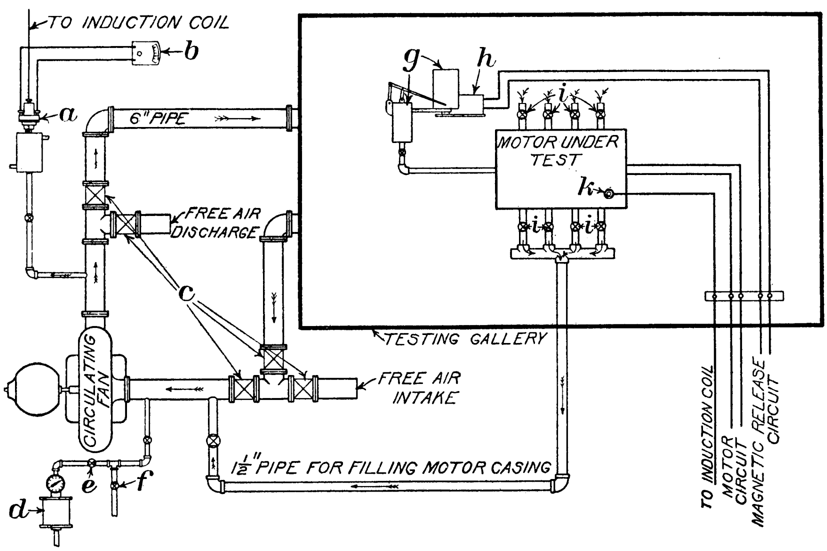


FIGURE 2.—Plan of testing apparatus: *a*, Gas-percentage indicator; *b*, millivoltmeter; *c*, 6-inch quick-closing gate valves; *d*, gas meter; *e*, gas-control valves; *f*, air-control valve; *g*, recording pressure indicator; *h*, release magnet for pressure indicator; *i*, 1½-inch quick-closing gate valves; *k*, spark plug for igniting mixture within casing.

circulation fan was tapped into the former at only one point. As a result the gaseous mixture probably passed through the motor casing in a more or less defined stream and left corners and crevices unfilled with the explosive mixture.

The gas-percentage indicator showed that the mixture passing through the motor contained 8.6 per cent of gas, and for this reason attention was for some time diverted from the true cause of the variations in pressure. The trouble was finally eliminated by providing in the motor casing four to six openings for the entering gas and by tapping the motor casing at four points for connection to the intake of the circulating fan. All these openings had quick-closing gate valves for isolating the casing from the gallery air and all exterior piping before the application of the spark. Figure 2 shows the arrangement of the pipe connections.

TEST PROCEDURE.

GENERAL METHOD.

In testing the motors the casings were completely filled and surrounded with various mixtures of gas and air. The mixture within the casings was exploded by an electric spark, and the character and extent of the discharged products of combustion and their action upon the surrounding gaseous mixture were noted. Means were provided for measuring the pressure developed by an explosion within the casing.

Tests were made with various percentages of gas in the casing mixture, with and without coal dust in the protective devices, and with several different points of ignition. Tests were also made while the motors were running at rated speed. In some of the tests the casing mixture was ignited by a spark from the brushes. In other tests the mixture was ignited by a spark plug.

DETAILS OF OPERATION.

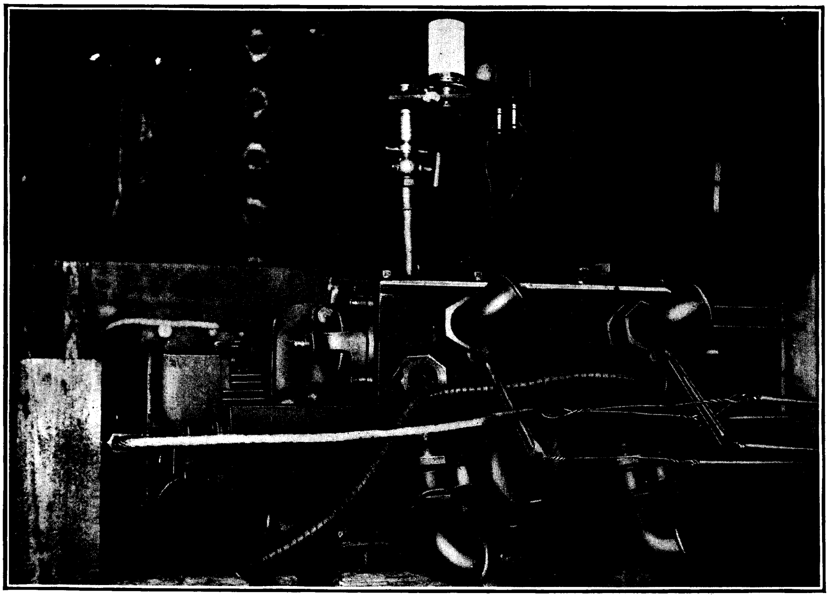
In making the tests arrangements were made for ignition at the desired point, a card was placed on the drum of the recording pressure indicator, and the gallery was closed. The circulating fan was then started and the valves set for circulating the mixture through the gallery. One hundred cubic feet of gas was then admitted to the gallery; the percentage indicator was then connected, and for several minutes the gas and air were mixed and circulated by the fan, gas being added as the indicator showed that it was required. The fan intake was then switched from the gallery piping to the pipe leading to the motor casing, and for several minutes the mixture was drawn into the casing and the percentage of gas was observed by the indicator. If the indicator showed that the proper mixture was not present, gas or air was added as needed.

If the gas-percentage indicator showed that the motor casing was properly "gassed," the gallery mixture was noted for one minute and then the mixture in the motor casing was noted for one minute more. If both gallery and casing mixtures proved to be correct, the fan was stopped and all valves leading to the gallery and to the motor casing were closed. The operator then took his position at the observation window directly above the motor and closed the switch that simultaneously ignited the mixture in the motor casing and released the drum of the recording pressure indicator.

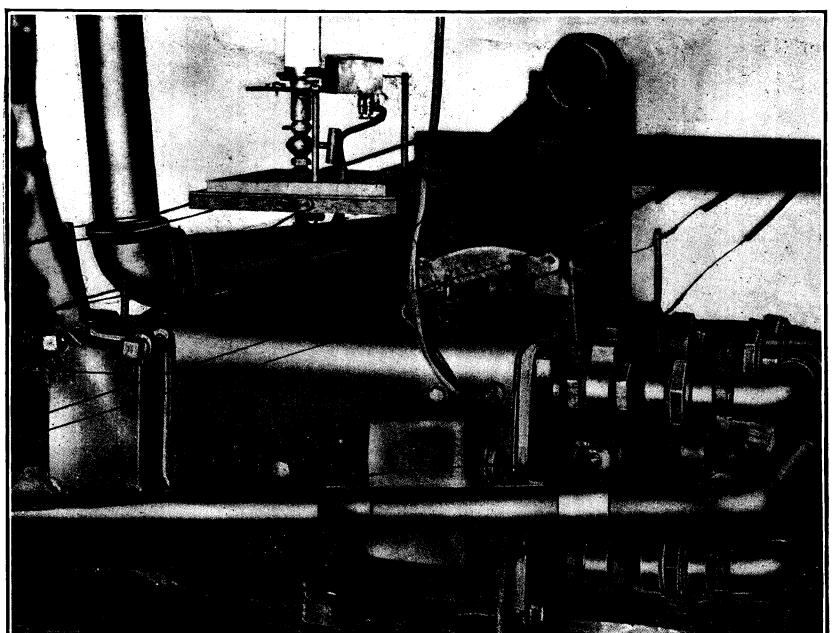
The gallery and the motor casing were thoroughly aired after each test.

PROTECTIVE DEVICES SUBMITTED.

For the purposes of this report the protective devices submitted for test have been classified under certain types, designated as type A, type B, etc. The characteristics of the various types are described below, and all test results are referred to the devices by the type letters.



A. MOTOR EQUIPPED WITH TYPE A PROTECTIVE DEVICE.



B. MOTOR EQUIPPED WITH TYPE E PROTECTIVE DEVICE.

TYPE A DEVICES.

The type A devices (Pl. III, *A*, *B*, and *C*, and fig. 3) consisted of three layers of gauze protected by a poppet valve. The motor used for testing was equipped with two of these devices, one of which was fastened to each side of that part of the motor casing that covered the commutator. (Pl. IV, *A*.)

TYPE B DEVICES.

The type B devices consisted of two unprotected layers of gauze having an exposed area of approximately 4 by 5½ inches. The motor that was submitted was provided with two of these devices, one of which was fastened to each side of that part of the motor casing that covered the commutator.

TYPE C DEVICES.

The type C devices consisted of five brass baffle plates (Pl. V, *A* and *B*, and fig. 9). The motor tested was provided with two of these devices, one of which was fastened to the motor casing on each side of the bearing on the commutator end of the machine.

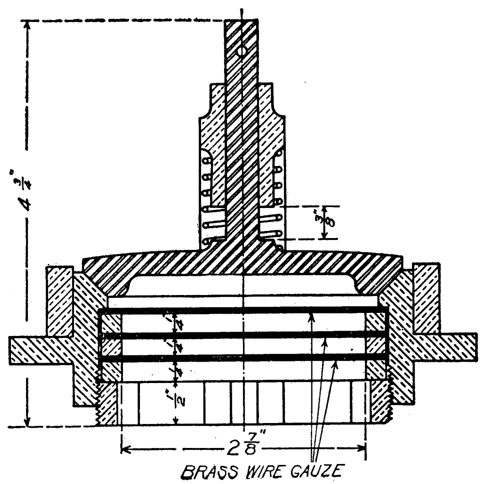


FIGURE 3.—Section of type A protective device.

TYPE D DEVICES.

The type D devices consisted of two sets of plates, one of which was located at each end of the motor casing, as shown in Plate V, *C*. Each set contained 43 plates of sheet iron 1 mm. in thickness and spaced 1 mm. apart by small pieces of the material from which the plates were made. The plates were in the shape of flat rings having an inside diameter of 30 cm. and an outside diameter of 40 cm. The total relief area of each set at the inside edges of the plates was 24 square inches and at the outside edges 34 square inches.

TYPE E DEVICES.

The type E devices consisted of two sets of gauze and baffle plates, one of which was placed at each side of the motor casing at the commutator end, as shown in Plate IV, *B*. Each set consisted of five sheets of 30-mesh brass gauze 4¼ by 6 inches, separated a distance of one-fourth inch by bronze spacers in each of which were 16 holes one-half by 1¾ inches. These sheets and spacers were inclosed by a bronze cover having a double baffle plate at the outlet (Pl. VI, *B*, *C*, and fig. 12). The whole was held to the motor casing by four $\frac{5}{8}$-inch cap screws.

RESULTS OF TESTS.

In the description of the results of the tests each type of protection is considered separately. Following the individual reports is a general discussion of the investigation as a whole.

MEANING OF "PUNCTURE."

For the sake of simplicity and to avoid confusion, the term "puncture" has been applied to the ignition of the gaseous mixture surrounding a motor casing by flames discharged from it.[a] In any test results in which "puncture" is reported the protective devices failed to perform their safeguarding function, as evidenced by the fact that the gaseous mixture outside the motor was fired by flames from within.

TESTS OF TYPE A PROTECTIVE DEVICES.

The type A devices were the first ones tested and some of the tests were merely preliminary. The investigation of these devices would no doubt be carried on differently if it were to be repeated in the light of present knowledge.

The design of the devices made it necessary to test under an unusually large number of conditions. As there were moving parts, tests with the parts in various positions were essential.

One hundred and ninety-one tests were made on these devices under forty-five different conditions. Ten or more tests were made under each of ten conditions and not less than two tests under any condition.

In the following tabulation are enumerated the conditions surrounding each test, the maximum pressure developed within the motor casing, the number of tests made, and the number of "punctures" which took place. For each set of conditions a characteristic pressure card is shown in figures 4, 5, 6, and 7.

DETAILS.

The details of the type A protective devices are so clearly shown in Plate III, and figure 3 that description is not necessary. Plate IV, *A*, shows the location of the devices upon the motor frame.

MOTOR.

The motor to which the type A protective devices were attached was a 250-volt, compound-wound, totally inclosed, direct-current motor arranged for gear connection to a coal-cutting machine. It was guaranteed to deliver 24 horsepower for 30 minutes, with a maximum temperature rise of 75° C.

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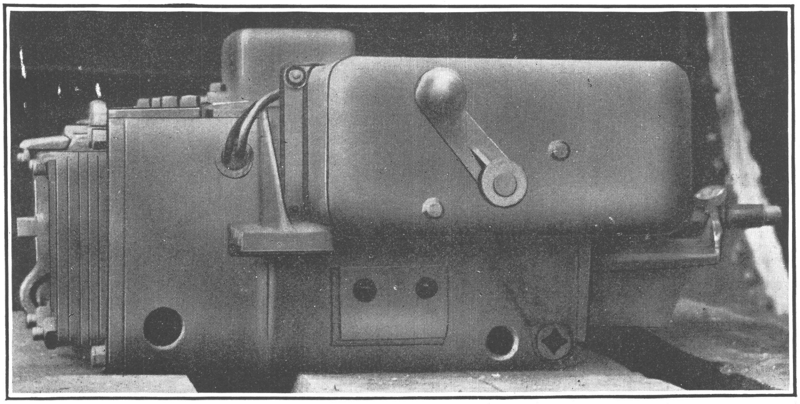
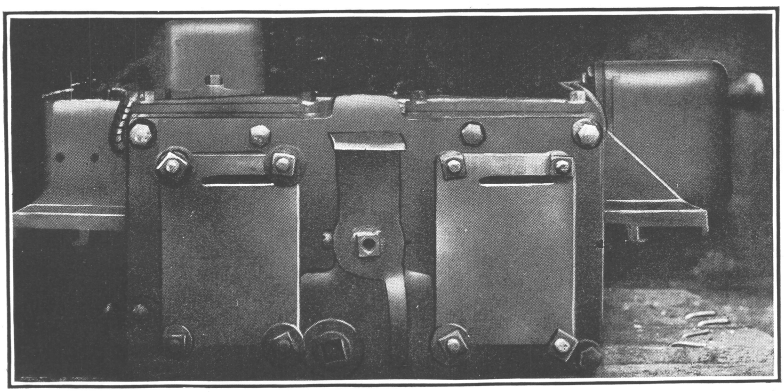
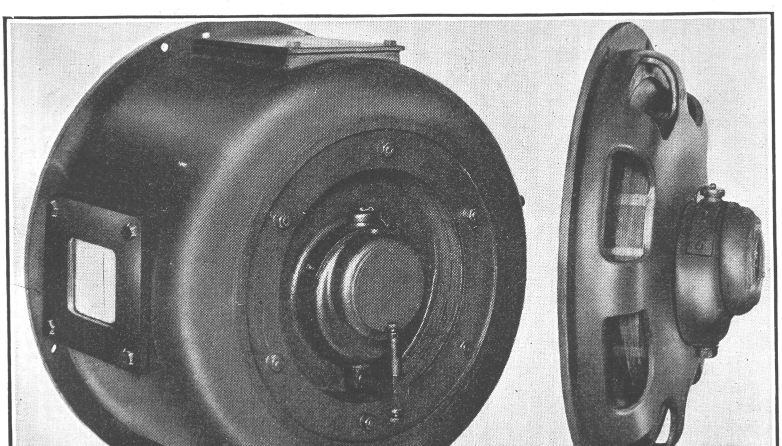
[a] This term has been used in the same sense by William Baum in his article "Fire-damp proof apparatus," General Electric Review, vol. 13, 1910, No. 9.



A. MOTOR EQUIPPED WITH TYPE C PROTECTIVE DEVICE, SHOWING FRONT VIEW OF BAFFLE PLATES.



B. SIDE VIEW OF THE MOTOR.



C. MOUNTING OF TYPE D PROTECTIVE DEVICE.

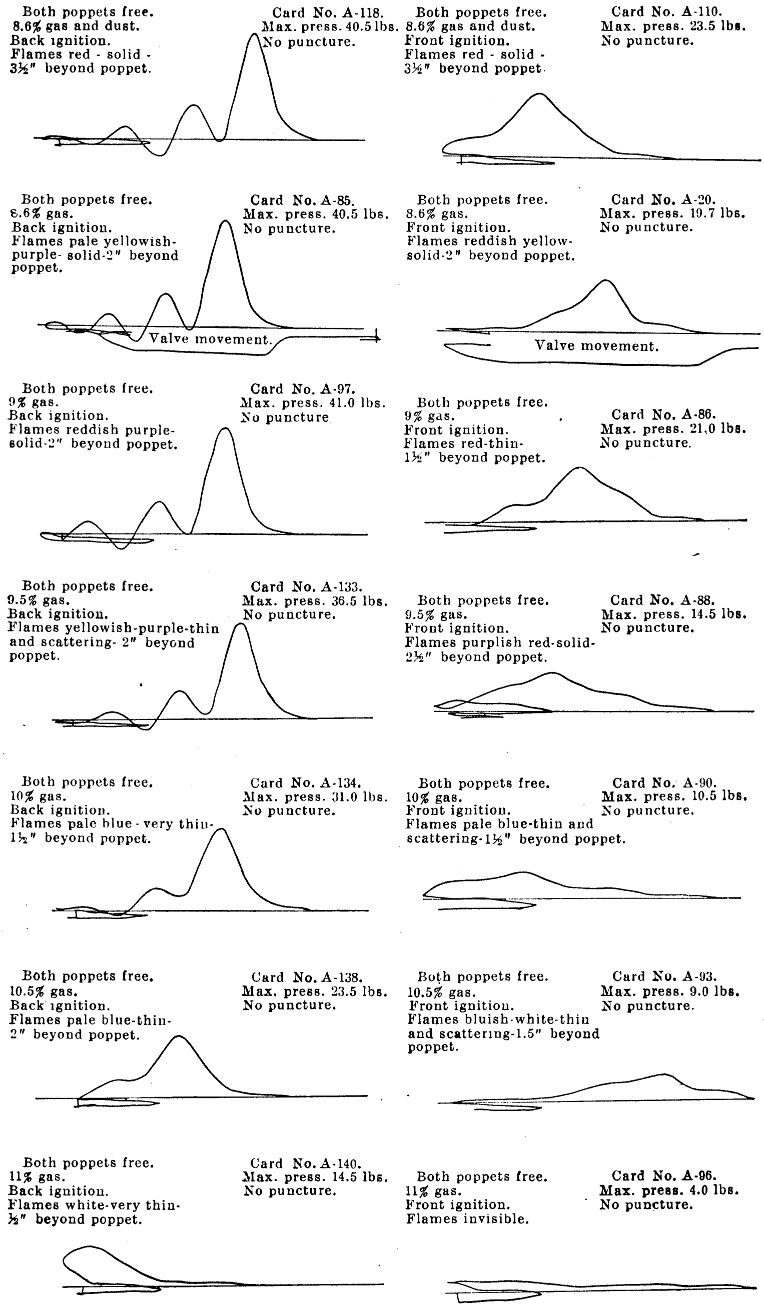


FIGURE 4.—Pressure diagrams for type A protective device.

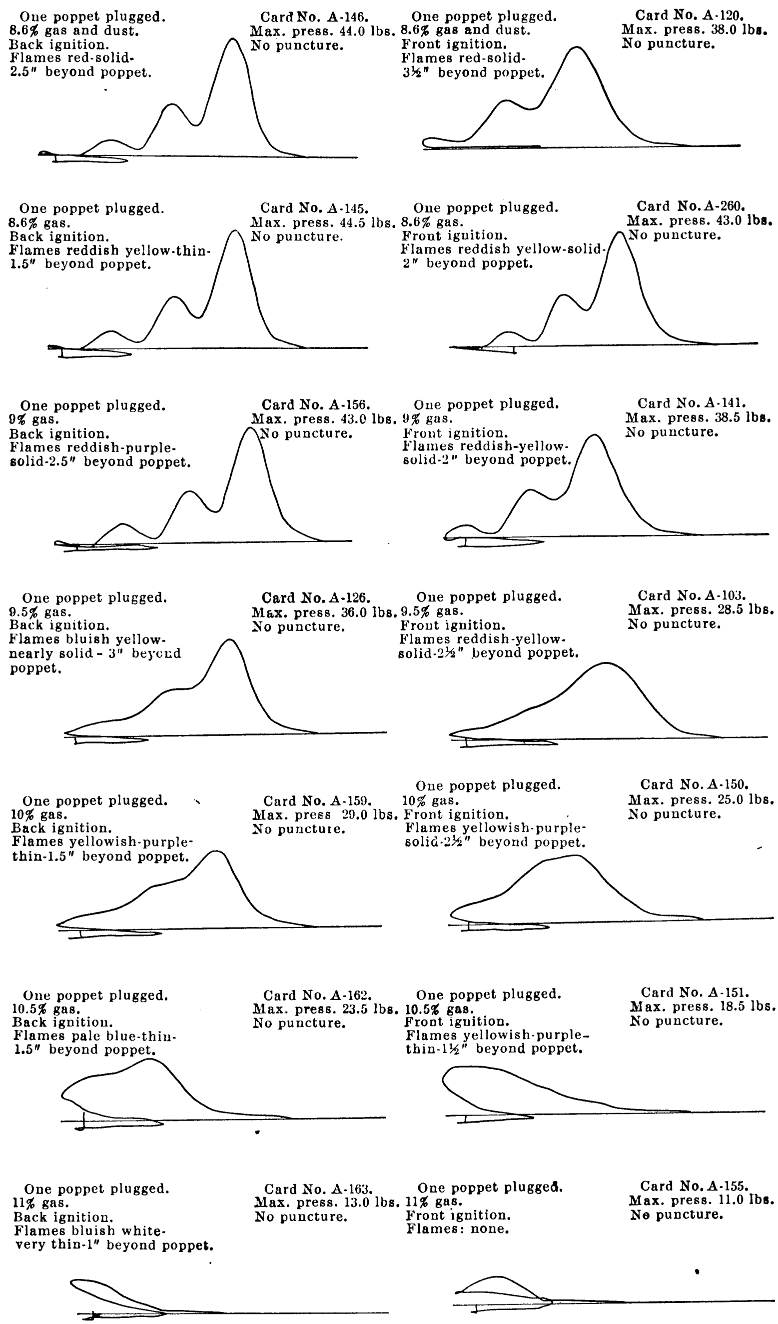
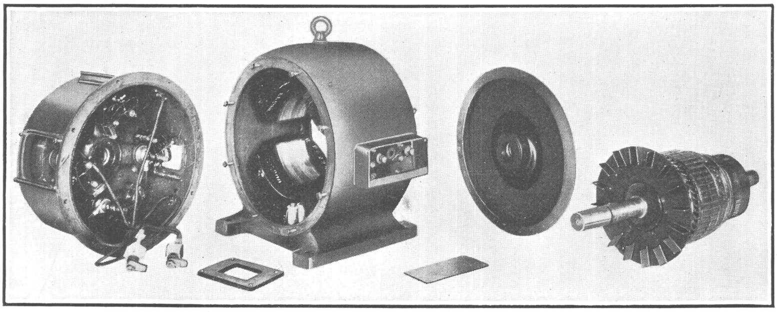
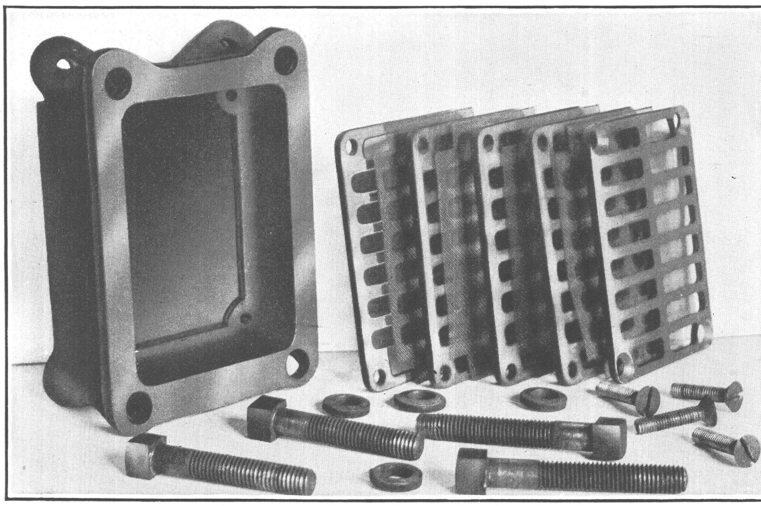


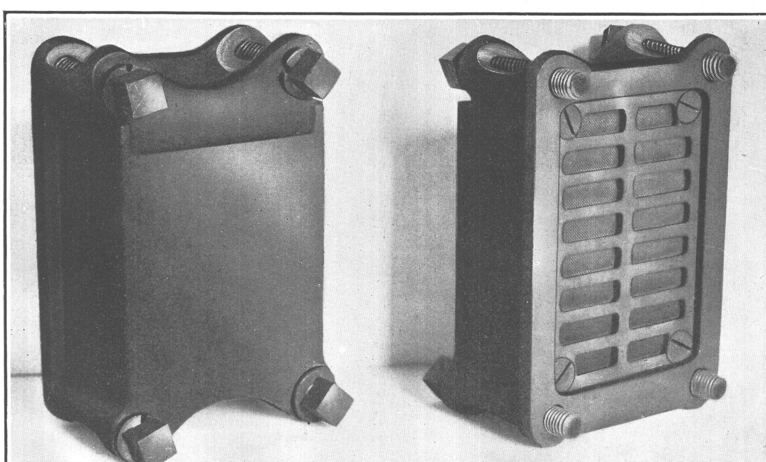
FIGURE 5.—Pressure diagrams for type A protective device.



A. MEMBERS OF MOTOR USED WITH TYPE D PROTECTIVE DEVICE.



B. PARTS OF TYPE E PROTECTIVE DEVICE.



C. FRONT AND BACK OF TYPE E PROTECTIVE DEVICE.

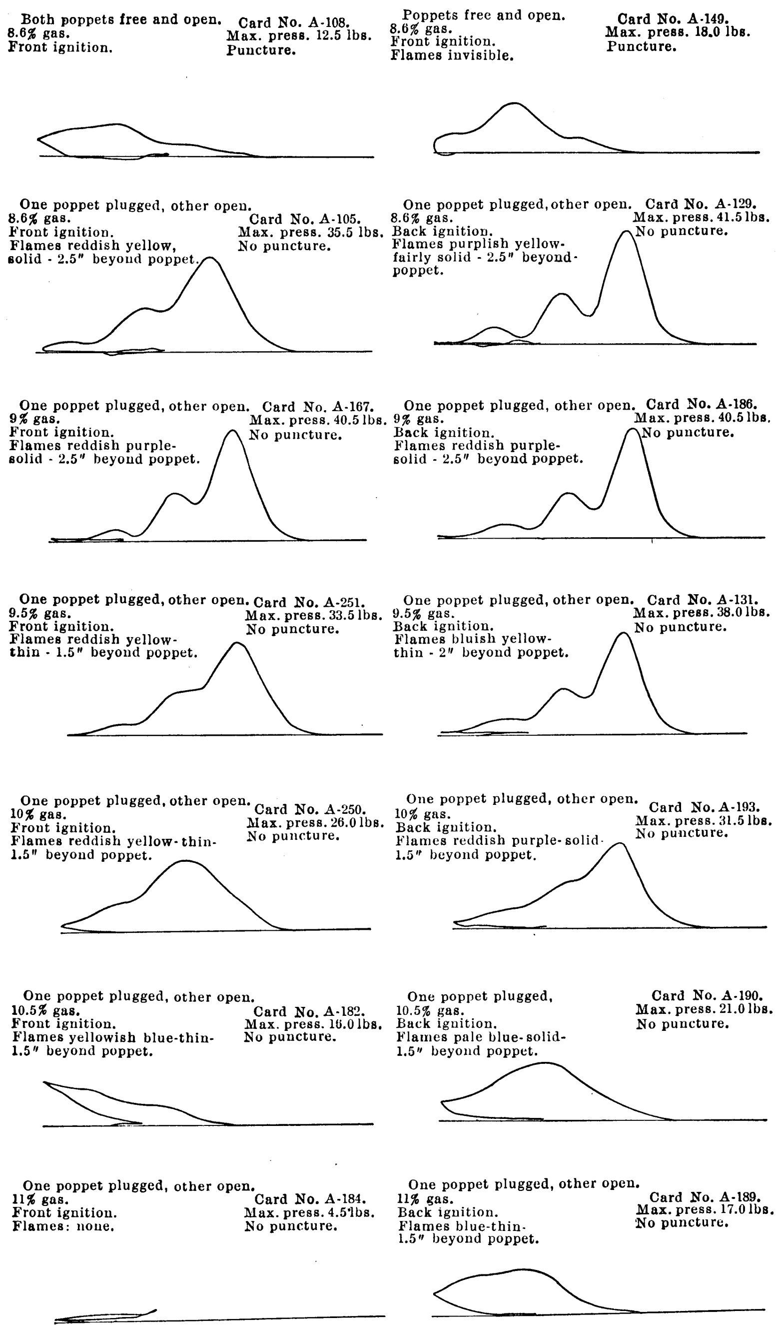


FIGURE 6.—Pressure diagrams for type A protective device.

Connection to the service line was made with plug leads, the sockets for which were inclosed in an iron box attached to the motor frame. Upon the motor frame were also mounted an iron box containing a reversing switch and a similar box containing a starting switch, contacts, resistance, and a single-pole fuse. None of these boxes communicated with the interior of the motor casing; none of them was gas-tight, and none of them was provided with explosion-proof protective devices. All conductors entering these boxes or the motor casing passed through holes bushed with rubber or hard fiber.

The unoccupied space within the motor casing had a total volume of 1.2 cubic feet. The combined minimum area of the relief openings in the protective devices was 5.22 square inches.

The motor was at rest in all the tests recorded.

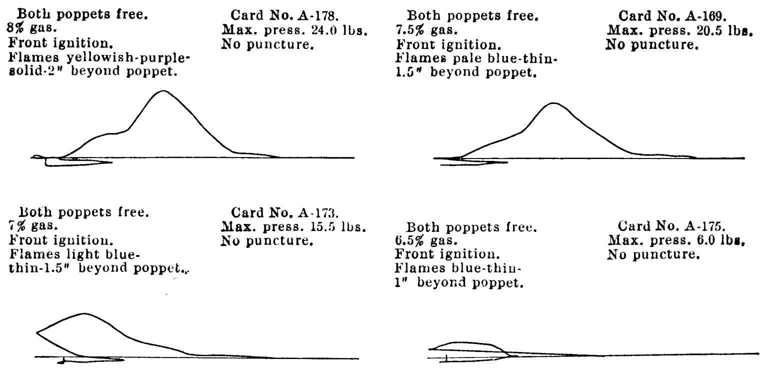


FIGURE 7.—Pressure diagrams for type A protective device.

IGNITION POINTS.

In the tabulated report, "Front ignition" refers to ignition from a spark plug screwed into the motor casing at a point directly above the commutator and near the protective devices. "Back ignition" refers to ignition from a similar spark plug screwed into the pinion end of the motor casing as far as possible from the protective devices.

POPPET CONDITION.

In the tabulation, under the heading "Poppet condition," the expression "both free" means that the poppet valves were closed but free to move as designed; "one plugged" means that one poppet valve was fastened in the closed position so that it could not move, whereas the other poppet was in its normal position and condition.

"Both free and open" means that the springs were removed from the valve stems and the poppets pulled open before the explosion within the motor casing was initiated. "One plugged, other open" means that one poppet valve was as specified under "one plugged," whereas the other was as specified under "both free and open."

FLAMES.

Flames were discharged through the protective devices in almost every test. Except in some of the "overgas" tests the flames were never less than 2 inches in length and often were longer. The maximum flame length was about 4 inches. The flames lasted only a fraction of a second and varied in color from pale blue to bright red.

TABLE 1.—*Results of tests of type A protective devices.*

Group No.	Poppet condition.	Gas percentage.	Ignition point.	Maximum pressure.	Outside flames.	Typical pressure diagram.		Number of tests made.	Number of "punctures."
						Card number.	Figure number.		
				Pounds per sq. in.					
1	Both free	8.6	Front	23.0	Yes	A-20	4	15	0
2	do	8.6	Back	43.5	Yes	A-85	4	12	0
3	do	9.0	Front	21.0	Yes	A-86	4	2	0
4	do	9.5	do	14.5	Yes	A-88	4	2	0
5	do	10.0	do	11.0	Yes	A-90	4	2	0
6	do	10.5	do	9.0	Yes	A-93	4	2	0
7	do	11.0	do	4.5	Yes	A-96	4	2	0
8	do	9.0	Back	41.0	Yes	A-97	4	2	0
9	do	9.5	do	36.5	Yes	A-133	4	2	0
10	do	10.0	do	31.0	Yes	A-134	4	2	0
11	do	10.5	do	25.0	Yes	A-138	4	3	0
12	do	11.0	do	18.0	Yes	A-140	4	3	0
13	do	8.0	Front	24.0	Yes	A-178	7	3	0
14	do	7.5	do	23.0	Yes	A-169	7	3	0
15	do	7.0	do	16.0	Yes	A-173	7	3	0
16	do	6.5	do	7.5	Yes	A-175	7	2	0
17	do	[a]8.6	do	27.5	Yes	A-110	4	10	[b]1
18	do	[a]8.6	Back	45.8	Yes	A-118	4	10	0
19	One plugged	8.6	Front	43.0	Yes	A-260	5	10	0
20	do	8.6	Back	44.5	Yes	A-145	5	10	0
21	do	9.0	Front	38.5	Yes	A-141	5	2	0
22	do	9.5	do	30.0	Yes	A-103	5	3	0
23	do	10.0	do	25.0	Yes	A-150	5	2	0
24	do	10.5	do	18.5	Yes	A-151	5	2	0
25	do	11.0	do	11.0	No	A-155	5	2	0
26	do	9.0	Back	43.0	Yes	A-156	5	2	0
27	do	9.5	do	38.0	Yes	A-126	5	2	0
28	do	10.0	do	33.0	Yes	A-159	5	4	0
29	do	10.5	do	25.0	Yes	A-162	5	2	0
30	do	11.0	do	14.5	Yes	A-163	5	2	0
31	do	[a]8.6	Front	47.0	Yes	A-120	5	10	0
32	do	[a]8.6	Back	47.0	Yes	A-146	5	12	0
33	Both free and open.	8.6	Front	18.0	Yes	A-108	6	3	3
34	One plugged, other open.	8.6	do	37.5	Yes	A-105	6	10	0
35	do	8.6	Back	45.5	Yes	A-129	6	10	0
36	do	9.0	Front	40.5	Yes	A-167	6	2	0
37	do	9.5	do	33.5	Yes	A-251	6	3	0
38	do	10.0	do	30.5	Yes	A-250	6	5	1
39	do	10.5	do	16.0	Yes	A-182	6	2	0
40	do	11.0	do	4.5	No	A-184	6	2	0
41	do	9.0	Back	41.0	Yes	A-186	6	2	0
42	do	9.5	do	39.0	Yes	A-131	6	2	0
43	do	10.0	do	31.5	Yes	A-193	6	2	0
44	do	10.5	do	21.0	Yes	A-190	6	2	0
45	do	11.0	do	17.5	Yes	A-189	6	2	0

[a] In this group of tests the figures in the column headed "gas percentages" are self-explanatory with the exception of "8.6 and dust." This means that finely ground coal dust was sifted into the protected devices before each test.

[b] The test in which "puncture" occurred was conducted in the same manner as the other nine tests of this series. The usual explosion inside the motor casing took place without causing a "puncture." All electrical connections with the motor casing were then broken and after an interval of several seconds the operator opened the quick-closing valves, by which the casing was filled with gas. The gallery exploded instantly. This "puncture" can not be charged against the protective devices, but is of interest as seeming to indicate that the presence of coal dust was its immediate cause. Probably the coal dust within the motor casing, although ignited by the explosion, could not burn because of the lack of oxygen. When this lack was supplied by the opening of the "gassing" valves, the coal dust took fire and ignited the gas in the gallery.

DISCUSSION OF TEST RESULTS.

GENERAL REVIEW.

Of 45 sets of conditions assumed, group 33 produced "punctures" in each of three tests made, and group 17 produced a single "puncture" out of ten tests made. During the earlier part of the investigation a "puncture" was obtained under the same conditions that prevailed in group 1, except that the percentage of gas in the motor casing could not be definitely determined, although it was known to be less than 8.6 per cent. No "puncture" that could be charged to defects in the design of the protective devices was produced in the 182 tests of the remaining 43 groups.

With the relief valves in their normal condition no "puncture" happened in any of the 80 tests in which the conditions were known and controlled, but one "puncture" happened under indeterminate conditions, as mentioned above.

PERFORMANCE OF THE DEVICES.

In order to produce an explosion outside a motor casing the gases discharged from the protective devices must raise the surrounding gaseous mixture to its ignition temperature. If in the tests the gases were discharged at a temperature lower than the ignition temperature of the gas—that is, if the protective devices fulfilled the function for which they were designed—no explosion could have taken place outside the motor regardless of how much heat was discharged. The presence of flames, however, showed that the temperature of the discharged gases was higher than the ignition temperature of the gaseous mixture surrounding the motor. Consequently, the temperature of the discharged gases must have been reduced by radiation to the surrounding gas without raising the latter to its ignition temperature, or "puncture" would have occurred.

The safety of a motor protected as in these tests, therefore, appears to depend upon the efficient dissipation of heat in the gaseous mixture surrounding the motor instead of upon the removal of the heat from the escaping gas by the protective devices; the gauzes obviously fail in their cooling functions since they do not prevent the passage of flames; therefore it is probable that even when no "puncture" occurs the escaping gases fail to ignite the surrounding mixture by only a small margin which might be overstepped by a slight variation in conditions.

The poppet probably assists in cooling the escaping gases by discharging them in a manner most conducive to rapid loss of heat, and it also serves to equalize the pressure on each side of the gauzes which would otherwise be torn from their fastenings by the explosion within the casing.

The unprotected parts of the relief valves are exposed to injury from falling material and careless handling, and, being easily accessible, are likely to be put out of adjustment through ignorance or carelessness.

THE EXPLOSIVE CONDITION.

The gaseous mixture that produces the most heat when burned contains 8.6 parts of gas and 91.4 parts of air. The greatest temperature and pressure is produced when such a mixture is burned or exploded most rapidly. The greatest amount of heat is discharged at one point when the gases are made to escape through a single protective device.

All the above conditions existed in the group 20 tests and yet "puncture" did not take place, although only one protective device was in service.

In each of the group 33 tests, with both protective devices in service, "puncture" occurred. The total heat produced was a maximum, but the temperature and pressure were both lower than in the group 20 tests.

In the group 35 tests the position of the poppet was the same as in the group 33 tests. The total heat was also the same, the temperature and pressure were higher, and the hot gases were vented through a single protective device, yet there was no "puncture." Card No. A–20 (fig. 4) shows that almost as soon as the explosion within the motor casing started the poppets moved to the same position that they occupied in the group 33 tests. It therefore appears that the conditions of radiation were better in the tests of group 35 than in those of group 33, probably because of the more rapid expansion of the discharged gases as they left the motor casing. In the single instance mentioned (p. 24) both poppets were closed and yet explosion occurred, In the group 38 tests the heat developed was not a maximum, yet one test gave an explosion with 10 per cent gas.

Since explosions occurred with poppets open, with poppets closed, with 8.6 per cent gas, with "overgas," with "undergas," with low pressure (12.5 pounds), and with comparatively high pressure (30.5 pounds), it is not possible exactly to define what constitutes the explosive condition for the type A protective device as applied to the particular motor tested.

STARTING BOX AND CONNECTIONS.

With safety devices on the motor casing it is hardly consistent to leave the starting box unprotected. A spark sufficiently large to ignite gas may be drawn every time the motor is started, and if gas is present the heat due to its explosion must be absorbed by something if ignition of surrounding gas is to be prevented.

Although it is not likely that the main connection plugs would be removed while current is passing through them, there is no absolute assurance to the contrary unless they are interlocked in a suitable manner with the starting switch.

TESTS OF TYPE B PROTECTIVE DEVICES.

The type B devices were not tested in the gallery because the information gathered from the test of the type A devices pointed to the almost certain failure of the type B protection. This consideration alone would have been insufficient to exclude the type B devices from test had the inadequacy of mechanical design of the devices not been manifest. Under the conditions that would surround such devices in practice, so large an area of unprotected gauze would be in danger of injury that would render the gauze of no avail as a safety device. The bureau's opinion was communicated to the manufacturers, who promptly withdrew their devices.

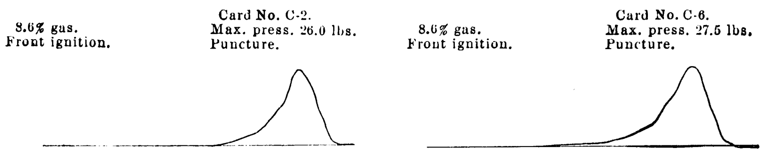


FIGURE 8.—Pressure diagrams for type C protective device.

TESTS OF TYPE C PROTECTIVE DEVICES.

The design of the type C devices was such that their failure was almost a certainty, but as the mechanical design was rugged the devices were submitted to a few tests in order to prove beyond a doubt that the devices were not suited to the purpose for which they were intended.

Only two tests were made upon these devices. The results of these tests were so conclusive that further investigation was considered unnecessary.

In the following tabulation are enumerated the conditions surrounding each test, the maximum pressure developed within the casing, the number of tests made, and the number of "punctures" which took place. For each test a characteristic pressure card is shown in figure 8.

DETAILS.

The details of the type C protective devices are shown in Plate V, *A* and *B*, and figure 9.

Each of these devices consisted of five brass baffle plates so disposed as to make a passage approximately 28 inches long with a cross-section of 4 inches by ¼ inch. This passage interposed three return bends and two right-angle bends in the path of the flame.

MOTOR.

The motor to which the type C protective devices were attached was a 250-volt, compound-wound, totally inclosed, direct-current motor arranged for gear connection to a coal-cutting machine. It was guaranteed to deliver 20 horsepower for 30 minutes, with a maximum temperature rise of 75° C.

Connection to the service line was made by leads provided with brass lugs for fastening to studs set in a wooden block on the outside of the motor casing. Studs and block were protected by a cast-iron cover bolted to the casing. Upon the motor frame was also mounted an iron box containing the starting switch, contacts, resistances, and a single-pole fuse. The box did not communicate with the interior of the motor casing. All conductors entering the box or the motor casing were bushed with fiber. The starting box was not provided with explosion-proof devices.

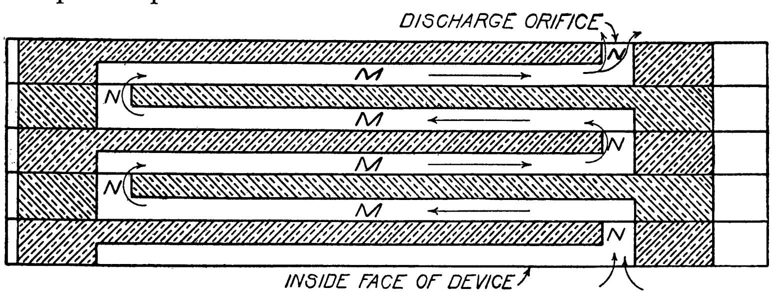


FIGURE 9.—Section of type C protective device. Area of cross section of opening at $M=1$ square inch; area of cross section of opening at $N=1\frac{1}{2}$ square inches.

The unoccupied space within the motor casing had a total volume of 0.68 cubic foot. The combined minimum area of the discharge passages in the protective devices was 2 square inches.

TEST CONDITIONS.

These tests were made with a mixture containing 8.6 per cent gas; the motor was at rest. The mixture inside the motor casing was ignited from a spark plug screwed into the casing at a point directly above the commutator and near the protective devices.

TABLE 2.—*Results of tests of type C protective devices.*

Group No.	Motor condition.	Gas percentage.	Ignition point.	Maximum pressure.	Outside flames.	Card No.[a]	Number of tests made.	Number of punctures.
1	At rest..	8.6	Front...	27.5	Yes.....	C-2, C-6	2	2

[a] See fig. 8.

DISCUSSION OF TEST RESULTS.

As a result of the tests the following conclusions are presented:

The type C protective device is not a safe design because the openings in the baffle plates are so large that their cooling effect is negligible and flames can easily pass through them. If gas is in the motor casing, the spaces between the baffle plates will also be filled with the mixture, as most of the gas will enter through these openings. Under such circumstances flame from within the motor casing will readily pass throughout the entire length of the passage between the baffle plates, being fed as it advances by the gas between the plates. Multiplication of the baffle plates would not improve the safety of the device.

TESTS OF THE TYPE D PROTECTIVE DEVICES.

Two hundred and thirty-six tests were made upon the type D devices under 25 different conditions. Ten or more tests were made for every condition in which the results of fewer tests were not conclusive. A smaller number of tests was made with the motor running, because the results were conclusive and because these tests were so severe that it was feared that the windings would break down before all the desired tests could be made.

Although the tests were made with great care, it was found impossible to check all pressures exactly, especially in "undergas" and "overgas" tests. Consequently, enough tests were made to obtain a sufficient number that checked consistently, and these are the only ones that are included in this report, as the other tests, being taken under unsatisfactory conditions, could add no information.

In the tabulation following are enumerated the conditions surrounding each test, the maximum pressure developed within the motor casing, the number of tests made, and the number of "punctures" that took place. For each set of conditions a characteristic pressure card is shown in figures 10 and 11.

DETAILS.

The details of the type D protective devices are clearly shown in Plates VI, *A*, and V, *C*, and the devices are described upon page 17. Plate III, *D*, shows how these devices are attached to the motor frame.

MOTOR.

The motor to which the type D protective device was attached was a 250-volt, 4-pole, shunt-wound, totally inclosed, direct-current motor, arranged for belt or direct connection to its load. The motor was guaranteed to deliver 10 horsepower continuously, with 40° C. rise in temperature, and was designed for general power purposes. No starting device was submitted for test with this machine. The

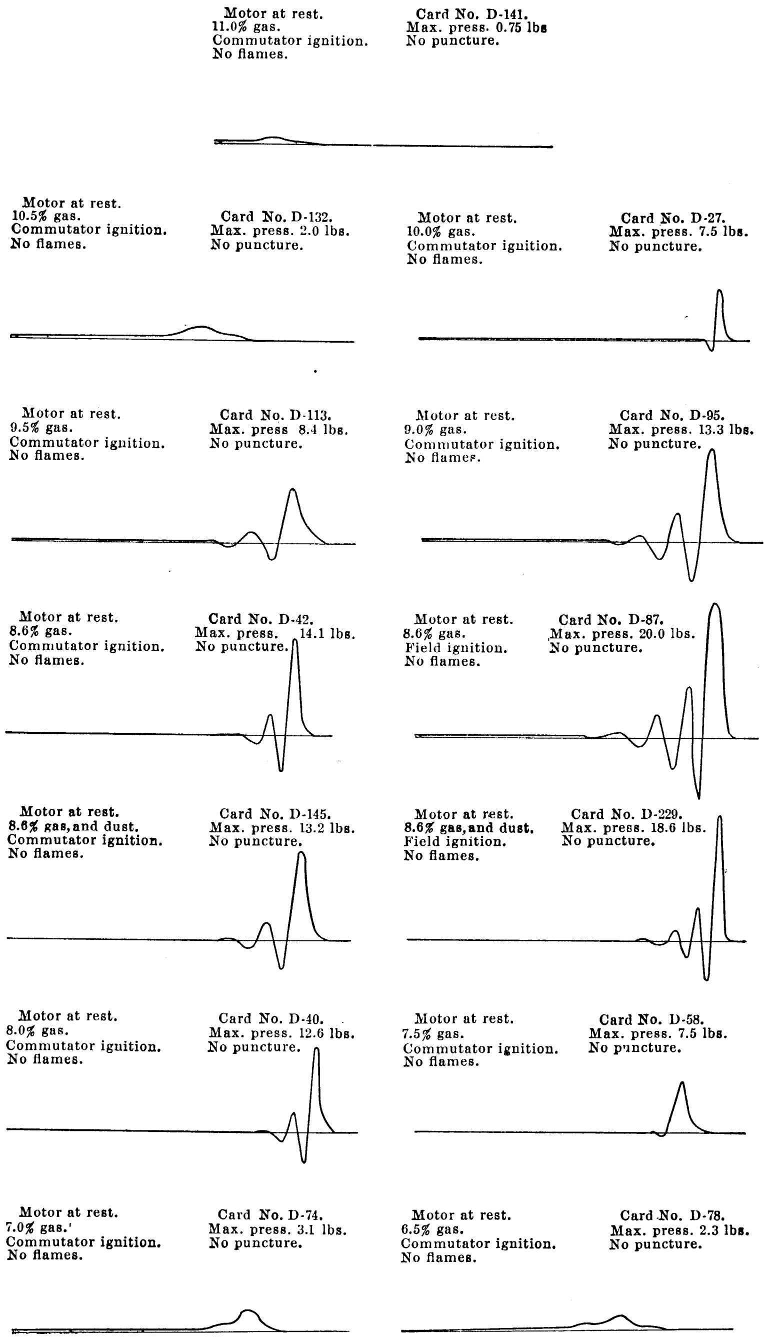


FIGURE 10.—Pressure diagrams for type D protective device.

unoccupied space within the motor casing had a total volume of 5.1 cubic feet. The combined minimum area of the relief openings was 48 square inches.

Connection with the service line was made to studs inclosed in an iron terminal box which was rigidly attached to the motor frame.

The leads from the service line were brought into the bottom of the terminal box through unbushed holes and soldered to brass lugs

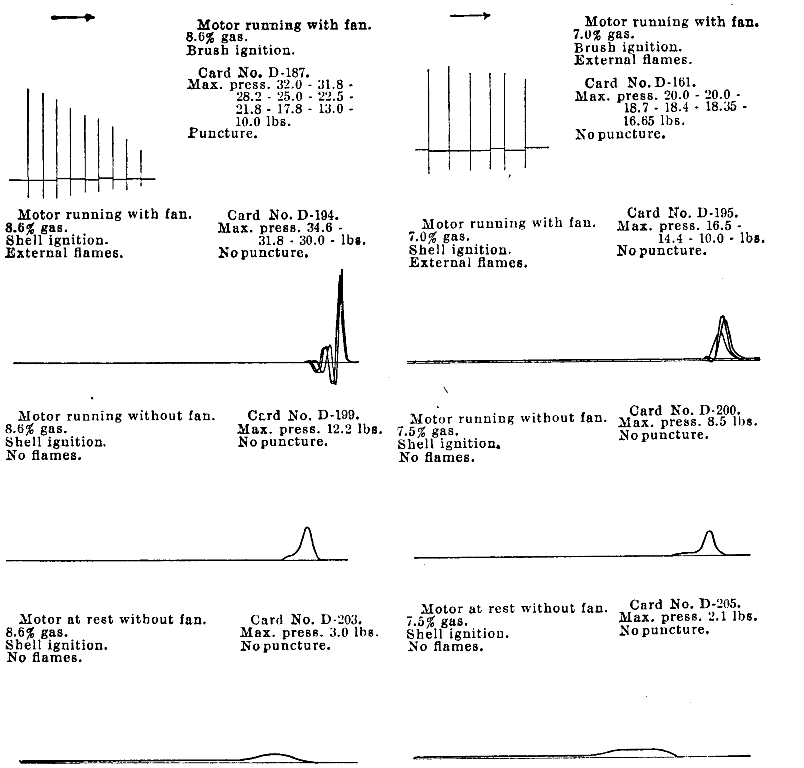


FIGURE 11.—Pressure diagrams for type D protective device.

drilled to fit the studs, to which they were fastened by a single nut. The studs passed through fiber bushings in the motor frame. The inner ends of the studs were protected by recessed porcelain blocks. The terminal box was not designed to be gas-tight. There was no communicating passage between the terminal box and the interior of the motor casing.

The armature shaft carried a fan (Pl. VI, *A*) so disposed with reference to the relief openings as to cause a considerable circulation of air through the motor casing when the armature was revolving at its rated speed. The fan consisted of 16 flat blades, 2½ by 1½ inches, mounted radially and in planes passing through the axis of rotation. The diameter inside the blades was 11½ inches. The outside diameter was 16½ inches.

On either side of the commutator a window of plate glass was fastened to the motor casing (Pl. VI, *A*). These windows were seemingly provided to permit the observation of brush sparking without opening the motor casing. One of the windows was cracked when the motor was received, but withstood the tests without further damage.

IGNITION POINTS.

In the tabulated report "commutator ignition" refers to ignition from a spark plug fastened near the commutator. "Shell ignition" refers to ignition from a spark plug screwed through the motor-casing at a point directly over the commutator. "Field ignition" refers to ignition at a point between the upper field coils near the commutator end of the armature core. "Brush ignition" refers to ignition by sparks from the brushes while the motor was running.

FLAMES.

Flames were discharged through the protective devices in all tests in which the motor was running with the fan in place, but no outside flames were observed in any other tests.

"AFTER-BURNING."

The term "after-burning," as used in this report, is applied to the appearance of flame at the inside edges of the protective plates from the burning of a gaseous mixture not within the casing at the time of the explosion. In "after-burning," gas was either drawn into the motor by the fan when the motor was running or forced in by atmospheric pressure as the dead gases within the motor casing cooled.

Fresh gas entered the casing after each explosion, whether the motor was running or not, but its subsequent ignition appeared to depend upon a delicate balance of several variables. Its bearing upon the safety of the motor submitted is not considered important, as it never occurred when the motor was running with the fan in place, and lasted only a few seconds when the motor was at rest.

TABLE 3.—*Results of tests of type D protective devices.*

Group No.	Motor condition.	Gas percentage.	Ignition point.	Maximum pressure.	Outside flames.	Typical pressure diagram. Card No.	Typical pressure diagram. Figure No.	Number of tests made.	Number of "punctures."	Speed of motor.
				Lbs. per sq. in.						*R.P.M.*
1	At rest, with fan.	8.6	Commutator..	14.1	No....	D-42	10	11	0	0
2	...do.......	8.6	Field..........	20.0	No....	D-87	10	13	0	0
3	...do.......	[a]8.6	Commutator..	13.2	No....	D-145	10	10	0	0
4	...do.......	[a]8.6	Field..........	18.6	No....	D-229	10	11	0	0
5	...do.......	9.0	Commutator..	13.3	No....	D-95	10	10	0	0
6	...do.......	9.5	.....do.........	8.4	No....	D-113	10	10	0	0
7	...do.......	10.0	.....do.........	7.5	No....	D-27	10	11	0	0
8	...do.......	10.5	.....do.........	2.5	No....	D-132	10	10	0	0
9	...do.......	11.0	.....do.........	0.8	No....	D-141	10	10	0	0
10	...do.......	8.0	.....do.........	12.6	No....	D-40	0	10	0	0
11	...do.......	7.5	.....do.........	7.7	No....	D-58	10	10	0	0
12	...do.......	7.0	.....do.........	3.1	No....	D-74	10	10	0	0
13	...do.......	6.5	.....do.........	2.3	No....	D-78	10	11	0	0
14	At rest, without fan.	8.6	Shell..........	3.0	No[b]...	D-203	11	2	0	0
15	...do.......	7.5	.....do.........	2.1	No[b]...	D-205	11	2	0	0
16	Running, with fan.	8.6	Brush..........	32.1	Yes...	D-187	11	9	2	[c]1,250
17	...do.......	7.0	.....do.........	20.0	Yes...	D-161	11	1	0	[c]1,250
18	...do.......	8.6	Shell..........	24.0	Yes...	D-194	11	1	0	[c]1,250
19	...do.......	8.6	.....do.........	29.6	Yes...	D-194	11	1	0	1,510
20	...do.......	8.6	.....do.........	34.6	Yes...	D-194	11	1	0	1,790
21	...do.......	7.0	.....do.........	16.5	Yes...	D-195	11	1	0	1,250
22	...do.......	6.5	.....do.........	11.2	Yes...	D-195	11	1	0	1,250
23	Running, without fan.	8.6	.....do.........	12.4	No[d]...	D-199	11	2	0	1,250
24	...do.......	8.6	.....do.........	12.2	No[d]...	D-199	11	1	0	1,500
25	...do.......	7.5	.....do.........	8.5	No....	D-200	11	1	0	1,250

[a] In this group of tests finely ground coal dust was sifted between the plates of the protective devices before each test.
[b] After-burning started at once and lasted for about 15 seconds.
[c] Normal speed.
[d] After-burning started at once and continued as long as the motor was running. Current was cut off the motor as soon as the explosion took place, but the motor did not stop for nearly a minute.

DISCUSSION OF TEST RESULTS.

GENERAL REVIEW.

One hundred and forty-one satisfactory tests were made with the motor at rest, and in none of these tests did "puncture" take place.

Thirteen tests were made with the motor running at normal speed with the fan in place. "Puncture" occurred in two of these tests, and probably would have taken place in at least three others if the tests had been continued to the limit.

Four tests were made with the motor running without fan. "Puncture" did not occur in any of these tests, but "after-burning" began immediately after the explosion, and would have continued indefinitely if the motor had not been stopped. The continuance of "after-burning" would have soon burned the insulation from the armature coils; but that the plates would have become sufficiently heated to allow the flame to pass out against the entering gas current is not certain.

In four tests, made with the motor at rest and the fan removed from the casing, there was no puncture nor were there external flames. The maximum pressure developed within the motor casing was only 3 pounds. "After-burning" followed the explosion, but lasted only a few seconds as the motor was not running.

Two tests were made with the fan in place and the motor running at greater than normal speed. "Puncture" did not occur in either of these tests, in each of which there were only three explosions within the motor casing.

PERFORMANCE OF THE DEVICES.

The protective devices appeared to be adequate for all conditions prevailing when the motor was at rest or when the motor was running without the fan, as under neither of these conditions were flames discharged through the protective devices.

When the motor was operating with the fan in position, reddish-yellow flames 4 to 6 inches in length were discharged through the protective devices at the commutator end.

The duration of these flames was short, and this probably accounted for their failure invariably to ignite the surrounding gaseous mixture, unless, perhaps, the first gases discharged from the casing were cooled by the plates below the ignition temperature of methane and drove away the explosive mixture immediately surrounding the relief openings, so that the flames which issued later were discharged into dead gas.

Despite the fact that there was no "puncture" until after at least five successive explosions inside the casing, "puncture" would almost surely occur in time if a sufficient supply of gaseous mixture were available.

If the motor were to be designed to operate without a fan, "after-burning" sufficient to destroy the insulation would take place if the rotation of the armature should produce a circulation of gas through the casing.

The value of this form of protection may be entirely destroyed by separating the plates by a small fraction of an inch. In the device tested the edges of the plates were not sufficiently protected from possible injuries of this character.

EFFECT OF THE FAN.

When the fan was in operation, it increased the effective resistance of the pulley end relief openings to the discharge of the products of explosion. This gave rise to higher pressures within the casing, and also caused more heat to be discharged from the commutator end openings. The fan also refilled the casing with the gaseous mixture after an explosion, and when the motor was sparking continuously, a succession of explosions resulted. These followed one another with more or less rapidity, depending upon the character of brush sparking. Under the conditions outlined above it would be merely a matter of time before the protecting plates would become so hot that they would no longer be effective.

Even with the fan removed, a certain amount of fan action was produced by the end conductors of the armature coils. This, however, did not result in a succession of explosions because "after-burning" set in at once; as fast as the gas was drawn in it was burned at the inner edges of the plates. This, as previously suggested, would result disastrously for the windings, but would not necessarily cause a "puncture."

The effect of the fan upon the pressure developed in the casing by explosion is shown very clearly by the tests listed under groups 18, 19, and 20, in which the pressure developed by the initial explosion varied from 24 pounds per square inch at 1,250 revolutions per minute (normal speed) to 34.6 pounds per square inch at 1,790 revolutions per minute.

TESTS OF TYPE E PROTECTIVE DEVICES.

Two hundred and sixty-eight tests were made on the type E devices under twenty-six different conditions. Ten or more tests were made under those conditions that were considered to be most severe, and one or more under all others. Fewer tests were made with back ignition in the "overgas" and "undergas" conditions because back ignition offsets the effect of more or less gas—that is, slow flame propagation.

Although the tests were made with great care, the results of tests made under the same conditions did not always check each other satisfactorily, and in such cases the tests were repeated until at least ten tests were obtained that checked each other within a reasonable percentage of variation. Only the latter tests are reported herein.

In some of the running tests more than one explosion took place within the motor. The total number of explosions within the motor casing was 272.

In Table 4 on page 36 are enumerated the conditions that surrounded each test, the maximum pressure developed within the motor casing, the number of tests made, and the number of "punctures" that took place. For each set of conditions a characteristic pressure card is shown in figures 13 and 14.

DETAILS.

The details of the type E protective devices are clearly shown in Plate VI, *B* and *C*, and figure 12. The devices are described on page 17. Plate IV, *B*, shows how these devices are attached to the motor frame. The safety device on the starting box was practically the same as those on the motor, differing only in details. The gauze sheets were smaller and the spacers were not so thick. The passages between the baffle plates were also smaller.

MOTOR.

The motor to which the type E protective devices were attached was a 250-volt, 4-pole, compound-wound, totally inclosed, direct-current motor designed to operate a coal-cutting machine by gear connection. The motor was rated at 20 horsepower for one hour, with a maximum temperature rise of 75° C.

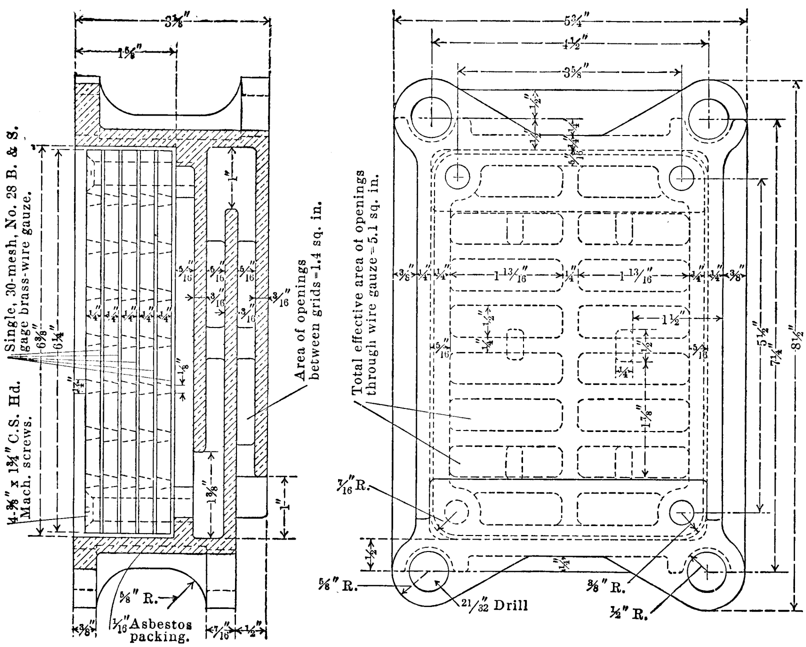


FIGURE 12.—Dimensions of type E protective device.

The motor leads were brought through a bushed hole in the casing to brass studs set in a hardwood block screwed to the outside of the casing. These studs were provided with lugs and thumbscrews and were protected by a cast-iron cover.

The motor was equipped with a starting box mounted on one side of the motor casing. It was a dial-type rheostat, with the resistance inclosed in a gas-tight nonremovable case, with contacts mounted on a slate slab. Terminals were also provided for a single fuse. The whole was screwed to a cast-steel base, and this in turn was screwed to the motor casing. The leads came through a bushed hole in the motor casing and through an unbushed hole[a] in the base of the

[a] This hole was plugged by the bureau's engineers before making the tests.

starting box. The box had a cast-steel cover, on which was mounted the control lever. The protective device was fastened to this cover. There was no communicating passage between the casing of the starting box and the casing of the motor. The unoccupied space within the motor casing was approximately 0.83 cubic foot, and the unoccupied space in the starting box was approximately 0.185 cubic foot. The combined minimum area of relief openings was 2.8 square inches.

IGNITION POINT.

In the tabulated report "front ignition" refers to ignition from a spark plug fastened at the commutator end of the motor—that is, the end nearest the relief openings. "Back ignition" refers to ignition from a spark plug fastened at the pulley end of the motor—that is, the end farthest away from the relief openings. "Brush ignition" refers to ignition by sparks from the brushes while the motor was running. "Side ignition" refers to ignition within the starting box from a spark plug placed at the side of the box.

FLAMES.

In no tests were any flames observed to issue from the protective devices.

TABLE 4.—*Results of tests of type E protective devices.*

Group No.	Motor condition.	Gas percentage.	Ignition point.	Maximum pressure.	Outside flames.	Typical pressure diagram.		Number of tests made.	Number of "punctures."
						Card No.	Figure No.		
				Pounds per square inch.					
1	At rest....	8.6	Front...	18.0	No....	E-106	13	10	0
2	.....do.....	8.6	Back....	27.4	No....	E-111	14	10	0
3	.....do.....	[a] 8.6	Front...	18.5	No....	E-220	13	10	1
4	.....do.....	8.6	Back....	29.7	No....	E-232	14	10	1
5	.....do.....	9.0	Front...	13.5	No....	E-125	13	10	0
6	.....do.....	9.5	...do.....	10.5	No....	E-154	13	10	0
7	.....do.....	10.0	...do.....	9.0	No....	E-170	13	10	0
8	.....do.....	10.5	...do.....	7.2	No....	E-203	13	10	0
9	.....do.....	11.0	...do.....	4.3	No....	E-211	13	10	0
10	.....do.....	9.0	Back....	23.0	No....	E-128	14	1	0
11	.....do.....	9.5	...do.....	18.5	No....	E-161	14	1	0
12	.....do.....	10.0	...do.....	16.0	No....	E-162	14	1	0
13	.....do.....	10.5	...do.....	11.0	No....	E-196	14	1	0
14	.....do.....	11.0	...do.....	9.2	No....	E-197	14	1	0
15	.....do.....	8.0	Front...	14.8	No....	E-129	13	10	0
16	.....do.....	7.5	...do.....	9.0	No....	E-147	13	10	0
17	.....do.....	7.0	...do.....	8.1	No....	E-183	13	10	0
18	.....do.....	6.5	...do.....	5.5	No....	E-188	13	10	0
19	.....do.....	8.0	Back....	22.0	No....	E-139	14	1	0
20	.....do.....	7.5	...do.....	20.6	No....	E-140	14	1	0
21	.....do.....	7.0	...do.....	12.1	No....	E-184	14	1	0
22	.....do.....	6.5	...do.....	9.7	No....	E-185	14	1	0
23	.....do [b]...	8.6	...do.....	32.7	No....	E-251	14	1	1
24	Running..	8.6	Front...	28.8	No....	E-234	13	4	0
25	.....do.....	8.6	Brush...	20.4	No....	E-239	13	4	0
26	.....do.....	8.6	Back....	47.2	No....	E-256	14	10	0
27	([c])	8.6	Side.....	7.4	No....	E-96-A	14	213	0

[a] In this group of tests finely ground coal dust was sifted into the protective devices before each test.
[b] In this group of tests one of the protective devices was purposely cut out of service, so that all of the products of combustion were discharged through one device.
[c] These tests were made upon the protective device that was attached to the starting box.

DISCUSSION OF TEST RESULTS.

GENERAL REVIEW.

Two hundred and forty-eight tests were made with the motor at rest, with a total of 248 explosions within the motor casing, and a "puncture" occurred only four times. One of these was due to a hole left in the casing by the manufacturers. The other three started from the relief valve, one at 8.6 per cent gas, with dust, front ignition; another at 8.6 per cent gas, without dust, back ignition; and the last at 8.6 per cent gas, without dust, back ignition, and one protective device cut out of service.

Twenty tests were made with the motor running, with a total of 24 [a] explosions within the motor casing. In none of these tests was there a "puncture."

In 213 of the 268 tests the starting box was tested by filling it with the gaseous mixture and igniting the mixture by means of a spark plug. In none of these tests was there a "puncture."

In no test were flames seen to issue from either of the relief valves on the motor itself or on the starting box.

PRESSURE IN THE MOTOR CASING.

The pressure developed within the motor casing varied with the character of the gaseous mixture and the point at which the ignition occurred. The operation of the motor at the time of the ignition also affected the pressure, raising the maximum observed pressure by 60 per cent or more. (Compare group No. 1 and group No. 24; also group No. 2 and group No. 26.)

In the group No. 25 tests, in which the mixture was ignited from a brush spark, ignition took place during the first revolution of the armature and therefore the full effect of running the motor was not obtained, as is attested by the fact that the pressures closely check those obtained with the motor at rest.

The pressure curves (figs. 13 and 14) show very plainly that the conditions that gave maximum pressure coincided with the conditions giving the maximum rate of flame propagation.

The conditions under which the highest pressure was developed were 8.6 per cent gas, back ignition, and the motor running (group No. 26). Under these conditions the maximum heat was developed and discharged from the relief openings in the minimum time. Under these conditions the flames within the motor seem to be most likely to reach the gaseous mixture surrounding it. The maximum pressure measured in this group of tests was 47.2 pounds, which was also the highest pressure measured during the entire investigation.

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[a] In some tests the motor casing was filled and exploded more than once.

PERFORMANCE OF THE DEVICES.

No "punctures" occurred while the motor was being tested with gas alone, excepting in a single test made with one of the protective

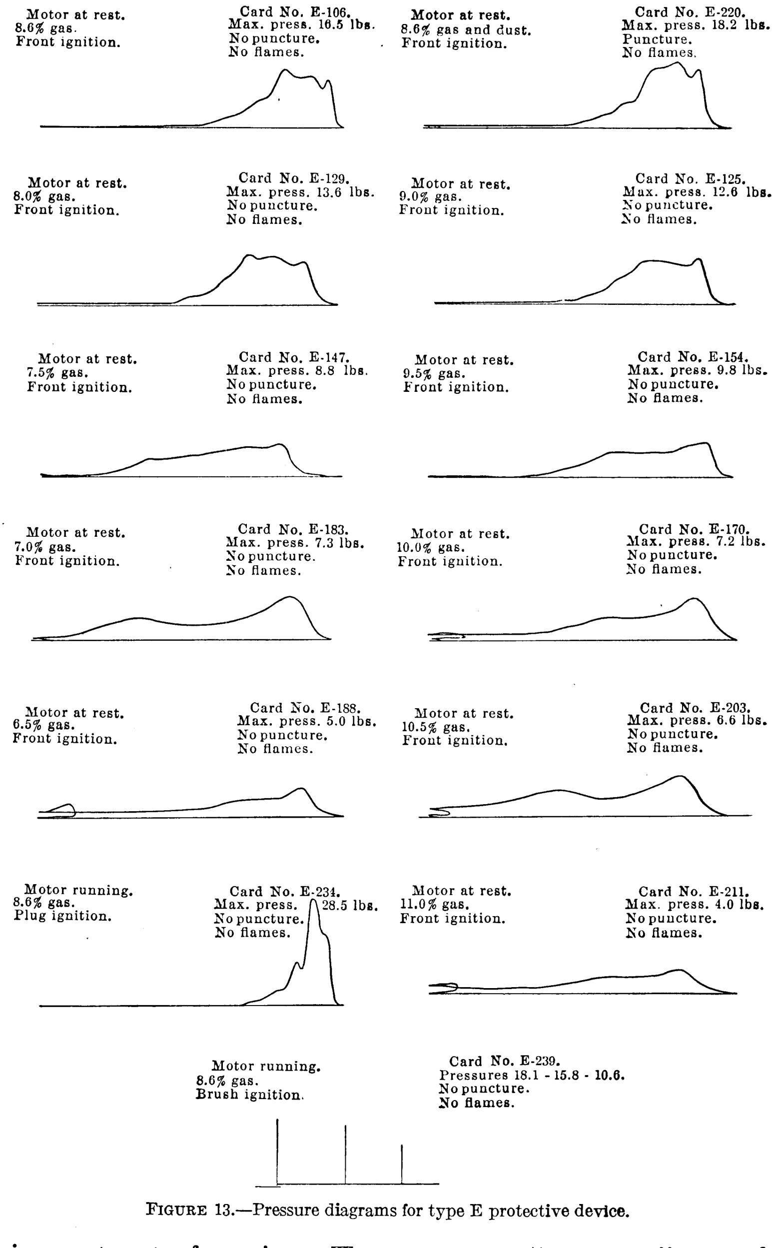

FIGURE 13.—Pressure diagrams for type E protective device.

devices cut out of service. There was one "puncture" out of 10 tests made under group No. 3 conditions. In that test no flames were observed to issue from the protective devices when the gaseous mixture inside the casing was ignited. The coal dust that had been sifted into the protective devices was driven out in a cloud and the explosion seemed to start from a point within this cloud. This

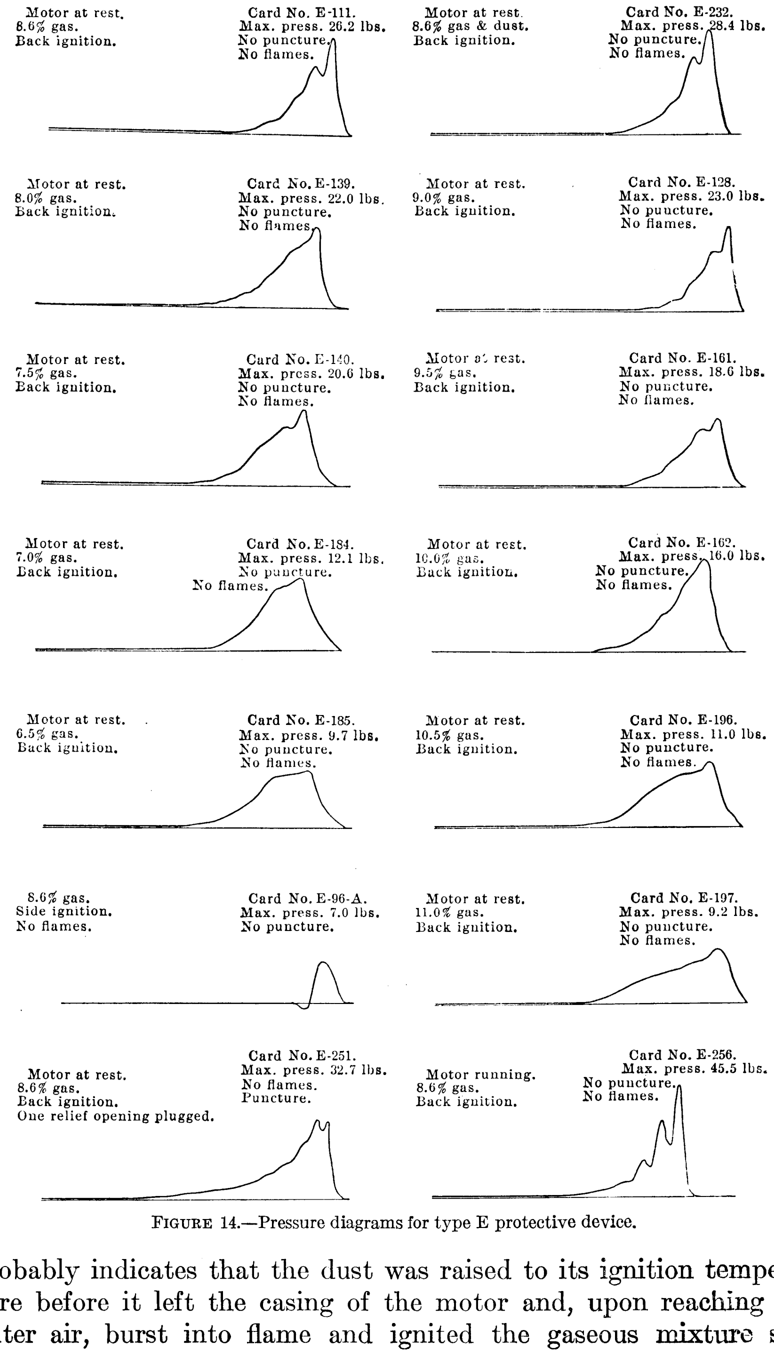

FIGURE 14.—Pressure diagrams for type E protective device.

probably indicates that the dust was raised to its ignition temperature before it left the casing of the motor and, upon reaching the outer air, burst into flame and ignited the gaseous mixture surrounding it. The pressure developed in the motor casing in the test in which there was a "puncture" was less than 40 per cent of the average maximum pressure produced in 10 other tests made with gas alone in which no "puncture" took place.

One "puncture" occurred in 10 tests made under group No. 4 conditions. The circumstances surrounding this "puncture" were practically the same as those surrounding the one just described. No flames were observed to issue from the motor. The dust was blown out in a cloud and ignition took place from the lower edge of the cloud when the latter was about 4 inches out from the relief opening in the protective device. The pressure developed within the motor casing in this test was about 65 per cent of the maximum pressure developed in 10 other tests made with gas alone in which no "puncture" happened.

The single test made under group No. 23 conditions caused all the gases to be discharged through a single protective device. No flames were seen to issue from the protective device. There was a small puff of dust blown out from it, and after an appreciable delay (possibly a second) the gaseous mixture ignited from a point just above the protective device. It is impossible to say that the presence of the small amount of dust was responsible for the explosion, but it appeared to be. The pressure obtained in this test was not excessive, being about 72 per cent of the average maximum pressure obtained in 10 tests of another group in which "puncture" did not occur.

The results obtained indicate that the type E devices give adequate protection when gas alone is used and both devices are in working order. When dust is present, however, the devices do not afford the protection which they are designed to give. The mechanical design of the devices seems to be well suited to the conditions under which they will be expected to operate.

GENERAL DISCUSSION.

REVIEW.

Of the five protective devices submitted, one was rejected without test, one failed completely in test, and each of the others failed under one or more conditions of test. One of the three devices last mentioned discharged flames in almost every test, another discharged flames only when the motor was running, and the third discharged no flames under any condition. The following tabulation compares the more important features of the devices and the results of the tests made upon them.

TABLE 5.—*General comparison of results of tests of five types of protective devices.*

Type.	Character of protection.	S. Unoccupied space in motor casing.	R. Minimum area of relief openings.	$\frac{R}{S}$	Maximum pressure, motor at rest 8.6 per cent gas, front ignition, 20° C., approximate.	Maximum pressure under any condition.	Discharge of flames.	Protection from mechanical injury.	Conditions under which "puncture" took place.
		Cubic feet.	*Square inches.*			*Pounds per square inch.*			
A	Gauze protected by a poppet valve.	1.2	5.22	4.35	20.0	47.0	Yes....	Unsatisfactory.	(a) Valves open, 8.6 per cent gas, front ignition, motor at rest. (b) One valve plugged, 10 per cent gas, front ignition, motor at rest.
B	Unprotected gauze.[a]	....	....	......	....	....	....	....	....
C	Baffle plates	0.68	2.0	2.95	26.0	27.5	Yes....	Good....	8.6 per cent gas, front ignition, motor at rest.
D	Plates......	5.1	48.0	9.4	[b]11.50	34.6	Sometimes.	Unsatisfactory.	8.6 per cent gas, brush ignition, motor running.
E	Subdivided gauze and baffle plates.	0.83	2.8	3.38	16.5	47.2	No.....	Good....	(a) 8.6 per cent gas and dust, front ignition, motor at rest. (b) 8.6 per cent gas and dust, back ignition, motor at rest.

[a] Not tested.
[b] The armature fan, even at rest, increased the effective resistance of these protective devices to the passage of gas. With the fan removed, but other conditions the same, the maximum pressure was only 3 pounds per square inch.

A weak point was found in each type of protection. In only 4 tests out of 191 did the type A devices prevent the passage of flames. Such a condition does not appear to be safe and, although few actual "punctures" occurred, the margin of safety seems to be narrow at all times. The successful operation of this type of protection appears to depend upon the dissipation of heat outside of the devices instead of, as was intended, within them. The margin of safety was overstepped when the maximum heat was discharged from the devices at a comparatively low pressure. This was accomplished by exploding the gaseous mixture within the motor casing while the protecting poppet valves were in the open position. Such a condition might exist in practice for the purpose of cooling the motor while in operation.

The type B and the type C devices were not at all suited to the purposes for which they were designed.

The failure of the type D devices was due more to the extremely severe conditions imposed by the motor design than to imperfections in the design of the devices themselves. It is hard to conceive of a device of reasonable size that could absorb the amount of heat produced by the continuous operation of such a motor in a gaseous atmosphere.

The weak point of the type E devices was their tendency to ignite coal dust deposited in the openings of the baffle plates outside the gauzes.

REQUIREMENTS OF EXPLOSION-PROOF PROTECTIVE DEVICES.

Explosion-proof protective devices should be so designed that flames can not be driven through them by an explosion of gas within the casing of the motor to which they are connected. They should also be so designed that coal dust can not enter them or, if allowed to enter, can not be discharged while ignited. Such devices should be very rugged in mechanical design or they should be completely protected from injury. They should also be so constructed and applied to the motor that they can not be detached from it without rendering the motor inoperative.

CASINGS OF EXPLOSION-PROOF MOTORS.

The casings of explosion-proof motors should be designed with the fewest possible number of openings. An ideal casing for this purpose would be one that had no openings whatever except those to which the protective devices were attached. The electrical conductors which enter such casings should be efficiently bushed with hard fiber or some other material that will make a strong and tight joint. If the amount of unoccupied space within the casing is made as small as possible the duty of the protective devices will be reduced to a minimum.

The factory tests to discover unprotected openings in the casings of explosion-proof motors should be as rigid and complete as any tests made upon the protective devices themselves. Several incidents that occurred during this investigation emphasized the importance of making such tests for tightness.

Although the type D motor was carefully examined before the test, an oil drain hole one-fourth inch in diameter escaped notice as it was filled solid with dirt and grease. On the first test this filling blew out and the flames that instantly followed caused an explosion of the gaseous mixture surrounding the motor. That single oversight made the protective devices of no avail.

In the case of the motor that was supplied with the type E devices the preliminary examination revealed two defects that had been overlooked by the manufacturers. These defects were repaired before beginning the tests, but a third defect escaped detection and later caused an explosion.

Obviously the most elaborate protective devices are useless if there are unprotected openings in the motor casing.

The starting boxes of explosion-proof motors should be protected with the same care as the motor casings.

THE DESIGN OF PROTECTIVE DEVICES.

The most satisfactory form of protective device is one that is capable of absorbing a large amount of heat. In order to do this the device must be constructed of a metal that is a good conductor of heat. A considerable amount of metal should be used and it should be so disposed as to offer a large amount of heat-absorbing surface to the flames without being itself raised to an unsafe temperature. The total area of protected openings through the wall of the motor casing should be as large as is consistent mechanically. There are two reasons for this arrangement. First, it permits the use of more heat-absorbing material, and, second, it decreases the maximum pressure developed. The lower the pressure the lower the temperature of the flame and the less heat is passed through the cooling devices in a given time. With a lower pressure the rate of flame propagation is slower; consequently, heat absorption is facilitated.

Use may be made of the fact that the advancing edge of the explosive wave is the most likely to be chilled because it passes through the coolest metal. If, then, the relatively cool dead gas produced by this means is passed through a comparatively long passage, like that between the baffle plates of the type E devices, subsequent flames will be cloaked with noncombustible gas and can cause no ignition.

Finally, the simpler and more rugged the design of such devices the better are they adapted for practical purposes. The devices should be so mounted as to render impossible the separation of plates or the rupture of gauzes. A splendid place for such devices would be entirely within the motor casing, with vent holes for the escaping gases.

LIST OF PERMISSIBLE EXPLOSION-PROOF MOTORS.

The Bureau of Mines is prepared to make tests of explosion-proof motors for the purpose of establishing a "permissible list" of such machines. Schedule 2 of the bureau describes the conditions under which such tests will be undertaken and states the fees charged for the work. This schedule may be obtained by applying to the Director of the Bureau of Mines, Washington, D. C.

PUBLICATIONS ON MINE ACCIDENTS AND TESTS OF EXPLOSIVES.

The following Bureau of Mines publications may be obtained free by applying to the Director, Bureau of Mines, Washington, D. C.

BULLETIN 10. The use of permissible explosives, by J. J. Rutledge and Clarence Hall. 1912. 34 pp., 5 pls.

BULLETIN 15. Investigations of explosives used in coal mines, by Clarence Hall, W. O. Snelling, and S. P. Howell, with a chapter on the natural gas used at Pittsburgh, by G. A. Burrell, and an introduction by C. E. Munroe. 1911. 197 pp., 7 pls.

BULLETIN 17. A primer on explosives for coal miners, by C. E. Munroe and Clarence Hall. 61 pp., 10 pls. Reprint of United States Geological Survey Bulletin 423.

BULLETIN 20. The explosibility of coal dust, by G. S. Rice, with chapters by J. C. W. Frazer, Axel Larsen, Frank Haas, and Carl Scholz. 204 pp., 14 pls. Reprint of United States Geological Survey Bulletin 425.

BULLETIN 26. Notes on explosive mine gases and dusts, by R. T. Chamberlin. 67 pp. Reprint of United States Geological Survey Bulletin 383.

TECHNICAL PAPER 4. The electrical section of the Bureau of Mines, its purpose and equipment, by H. H. Clark. 1911. 12 pp.

TECHNICAL PAPER 6. The rate of burning of fuse as influenced by temperature and pressure, by W. O. Snelling and W. C. Cope. 1912. 28 pp.

TECHNICAL PAPER 7. Investigation of fuse and miners' squibs, by Clarence Hall and S. P. Howell. 1912. 19 pp.

TECHNICAL PAPER 11. The use of mice and birds for detecting carbon monoxide after mine fires and explosions, by G. A. Burrell. 1912. 15 pp.

TECHNICAL PAPER 12. The behavior of nitroglycerin when heated, by W. O. Snelling and C. G. Storm. 1912. 14 pp., 1 pl.

TECHNICAL PAPER 13. Gas analysis as an aid in fighting mine fires, by G. A. Burrell and F. M. Seibert. 1912. 16 pp.

TECHNICAL PAPER 17. The effect of stemming on the efficiency of explosives, by W. O. Snelling and Clarence Hall. 1912. 20 pp.

TECHNICAL PAPER 18. Magazines and thaw houses for explosives, by Clarence Hall and S. P. Howell. 1912. 34 pp. 1 pl.

TECHNICAL PAPER 19. The factor of safety in mine electrical installations, by H. H. Clark. 1912. 14 pp.

TECHNICAL PAPER 21. The prevention of mine explosions, report and recommendations, by Victor Watteyne, Carl Meissner, and Arthur Desborough. 12 pp. Reprint of United States Geological Survey Bulletin 369, revised.

MINERS' CIRCULAR 2. Permissible explosives tested prior to January 1, 1911, and precautions to be taken in their use, by Clarence Hall. 1911. 12 pp.

MINERS' CIRCULAR 3. Coal-dust explosions, by G. S. Rice. 1911. 22 pp.

MINERS' CIRCULAR 4. The use and care of mine-rescue breathing apparatus, by J. W. Paul. 1911. 24 pp.

MINERS' CIRCULAR 5. Electrical accidents in mines; their causes and prevention, by H. H. Clark, W. D. Roberts, L. C. Ilsley, and H. F. Randolph. 1911. 10 pp., 3 pls.

MINERS' CIRCULAR 6. Permissible explosives tested prior to January 1, 1912, and precautions to be taken in their use, by Clarence Hall. 1912. 20 pp.

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