Bureau of Mines
Report of Investigations 4904

A STUDY TO DETERMINE FACTORS CAUSING PRESSURE PILING IN TESTING EXPLOSION-PROOF ENCLOSURES

BY E. J. GLEIM AND J. F. MARCY

United States Department of the Interior—August 1952

A STUDY TO DETERMINE FACTORS CAUSING PRESSURE PILING IN TESTING EXPLOSION-PROOF ENCLOSURES

BY E. J. GLEIM AND J. F. MARCY

Report of Investigations 4904

UNITED STATES DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary
BUREAU OF MINES
J. J. Forbes, Director

Work on manuscript completed April 1952.

August 1952

A STUDY TO DETERMINE FACTORS CAUSING PRESSURE-PILING IN TESTING EXPLOSION-PROOF ENCLOSURES

by

E. J. Gleim[1/] and J. F. Marcy[1/]

CONTENTS

ILLUSTRATIONS

1/ Electrical engineer, Bureau of Mines, Pittsburgh, Pa.

INTRODUCTION

An important phase in the Bureau of Mines investigation of electrical machines designed for operation in gassy coal mines is testing enclosures of electrical components for explosion-proof qualities. In brief, this testing consists of filling and surrounding the enclosure with an explosive atmosphere of methane and air and then igniting the atmosphere within the enclosure to determine: (1) Whether the resulting explosion is confined without discharge of flame; (2) whether the enclosure walls are permanently distorted; and (3) whether excessive pressures are developed within the enclosure.

Ordinarily, the pressures encountered in routine testing do not exceed 100 pounds per square inch gage. Hence, the designer of the machine does not have too much difficulty in taking corrective measures to prevent flame discharge and distortion of the enclosure. Occasionally, however, the explosion pressures greatly exceed 100 pounds. Then the problem of the designer may not be solved so readily. From experience over the years, the testing personnel often can predict that certain construction will result in high pressures, but, only in a very general way, has it been possible to advise designers what modifications might be made to reduce the explosion pressures to normal values. For example, if high pressures were developed in a motor starter having a partition with an opening through it, some enlargement of the opening may appear to be the logical procedure, but it has not been possible to give information concerning the exact amount the opening should be enlarged to prevent development of high pressures.

Because of this lack of knowledge of the factors that have a bearing upon pressure piling, a research project was undertaken in the expectation that data of practical value to the machine designer would be derived.

HISTORICAL BACKGROUND

The effect currently known as pressure piling was first systematically investigated by Beyling.2/ Extensive tests conducted from 1903 to 1906 to determine the flame- and explosion-proof qualities of commercial enclosures for electrical apparatus and motors showed that very violent and destructive explosions occurred in certain types of enclosures. Such enclosures were usually the type in which the free internal space was divided into separate connecting compartments. Beyling's simple explanation of the phenomenon, which was essentially correct but not entirely complete, was as follows:

1. Following ignition, some of the gas mixture ahead of the flame front is forced through the communicating passageway into the adjoining compartment.

2/ Beyling, E., [Tests for Determining the Safety of Specially Protected Electric Motors and Apparatus Against Explosion from Firedamp]: Glückauf, vol. 42, 1906.

2. Pressure increases in this compartment above the initial atmospheric pressure, hence the term "pressure piling."

3. The compressed-gas mixture is finally ignited by the flame projected from the ignition compartment.

4. The explosion pressure observed is directly related to the degree of compression before ignition.

The following conclusions are drawn from tests by Kirby[3] to determine the relation of flame movement to the pressure rise in a methane-air explosion:

1. Time of maximum pressure is identical to that of total inflammation of the mixture.

2. Critical length to cross section of an enclosure to produce vibratory movement in flame propagation.

3. Speed of the flame front is nonuniform (0 to 20 meters per second).

From a study of photographs by Grice and Wheeler[4] of the flame movement in coupled spheres as related to pressure curves, the following conclusions were drawn:

1. Rapid rise in pressure is due to the turbulence of the gas and to the relative size of the ignition source (flame) to the volume of the compartment. Both factors increase with the increase in ratio of the volumes of the coupled spheres, provided, of course, that ignition be in the larger sphere.

2. Although the maximum explosion pressure is directly proportional to the initial pressure of the gas mixture, as correctly assumed by Beyling, the rapidity of rise in pressure is, in contradiction to Beyling, definitely retarded by increase in initial pressure.

Photographs of flame-movement and explosion-pressure curves by Coward and Wheeler[5] show that the motion of flames in long tubes where the ratio of length to diameter is of the order of 100 to 1 accelerates rapidly and becomes vibratory. The nature of this vibratory propagation is akin to that of resonance of a gas column. The frequency of vibration of the flame was found to correspond to pressure fluctuations. The frequency of the vibration obtained experimentally checked with that obtained theoretically from the assumption of resonance. The frequency of vibration also could be detected audibly by the pitch of the explosion noise.

3/ Kirby, W. A., Explosion in Closed Cylinders: Safety in Mines Research Board, Technical Staff Lecture, Oct. 25, 1926, 14 pp.

4/ Grice, C. S. W., and Wheeler, R. V., Firedamp Explosions Within Closed Vessels: Pressure Piling: Safety in Mines Research Board Paper 49, March 1928, 26 pp.

5/ Coward, H. F., and Wheeler, R. V., The Movement of Flame in Firedamp Explosions: Safety in Mines Research Board Paper 82, June 1933, 59 pp.

In further tests with a tube 106 feet in length by 1 foot in diameter provided with 11 partition plates each with a 4-inch-diameter hole, extremely high flame propagations of about 2,000 feet per second were observed. The cumulative effect of each compartment on the next is to cause an extremely high rate of combustion of the gas by increasing the turbulence and the violence of the flame projected into succeeding compartments. In other tests where solid explosives were used for ignition, speeds of 6,000 feet per second were observed. Many of the latter characteristics of flame propagation are typical of true detonation. However, it differs from true detonation in that its rate of propagation has no definite constant value, so that at best this represents only quasi-detonation. The following limiting mixture - $CH_4 + 4O_2 + 4N_2$ - for detonation is given by Jost.6/ This mixture has twice the concentration of oxygen as that of air. Detonation pressure for gases is about twice as large as ordinary pressures without detonation.

BUREAU OF MINES TEST EQUIPMENT AND PROCEDURE

Test Box

This box or enclosure is shown in figure 1. It is constructed of 1/2-inch-thick steel plates. The joints between the bottom, side, and end plates are welded. For additional strength, the corners are reinforced externally with steel braces. Airtightness of the box is comparable to that found in commercial explosion-proof enclosures. Four channels have been machined in the box and cover to fit 12-1/2-inch-square steel removable partition plates. This permits the volume of the box to be divided into two parts having the following ratios: (a) 1:1, (b) 5:3, (c) 3:1, and (d) 7:1. Five partition plates with the following size holes centrally located were used: (a) 10-inch-diameter, (b) 8-inch-diameter, (c) 4-inch-diameter, (d) 4-inch-square, and (e) 2-inch-diameter.

Figure 1 shows the location of the pressure gages, point of ignition, and gas and thermal conductivity meter connections.

Pressure-Recording Equipment

The pressure gages employed are the strain-gage type. Gages in the ranges of (a) 0 - 150 pounds per square inch, (b) 0 - 300 pounds per square inch, and (c) 0 - 500 pounds per square inch were used. Gage natural frequency is above 2,000 cycles per second with a 2-millisecond response to a step-gradient pressure. These gages consist of four 300-ohm-resistance wire elements arranged in the form of a Wheatstone bridge. Pressure applied to a diaphragm to which the strain elements are attached produces unbalance in the bridge, which varies directly with the applied pressure. The bridge unbalance or output voltage is about 50 millivolts for these gages, at rated input voltage of 18 volts and at full pressure range. This output voltage is enough to be recorded directly by a Dumont 304H oscilloscope with maximum sensitivity of 10 millivolts per inch deflection. The gages were operated at a carrier frequency of 10,000 cycles per second. This proved more convenient than direct-current operation because

6/ Jost, W., Explosion and Combustion Processes in Gases; McGraw Hill Book Co., Inc., New York, N. Y., trans. by Huber O. Croft, 1946, 621 pp.

of greater ease in null balancing and calibration. The pressure curves obtained photographically are those of the 10,000-cycle per second carrier modulated by the output signal voltage from the gage under pressure. The pressure at any instant is given by the amplitude of the double envelope. The symmetry of this double envelope is a measure of the adequacy of the carrier frequency, which is considered high enough for 2,000-cycle-per-second frequency response. The time base of the pressure curve is obtained by the internal sweep of the oscillograph. This sweep is actuated from a double-pole switch, which triggers the sweep at the instant the ignition coil is energized. Delay in the sweep, when needed, is provided by use of a relay in the sweep circuit. A time base of 60 cycles per second obtained at the oscillograph is used for time calibration.

Test Procedure

Pittsburgh natural gas (analysis, approximately 91 percent CH_4; 8 percent C_2H_6; and 1 percent N_2) was used in these tests. A thermal-conductivity meter measured the concentration of gas. A 9.5-percent mixture of gas was found to produce the highest explosion pressure so this mixture was used in all subsequent tests. The gas mixture was ignited along the central axis of the box at one of the seven numbered positions shown in figure 1. The two pressure gages and the center of the holes in the five partition plates were located along the same central axis of the box. An explosion-proof blower was used to circulate the fresh mixture. By means of the valve arrangement and an auxiliary blower with a capacity of several hundred cubic feet per minute, the box was readily purged after the explosion and a fresh mixture of gas and air admitted.

EXPERIMENTAL TEST DATA

No Partition

Gage position 1			Gage position 2	
Maximum pressure, p.s.i.	Time maximum pressure, milliseconds	Ignition position	Maximum pressure, p.s.i.	Time maximum pressure, milliseconds
74	300	1	-	-
78	220	4	80	250
74	300	7	-	-

Ten-Inch-Diameter Opening Partition

Compartment ratio	Gage position 1		Ignition position	Gage position 2	
	Maximum pressure, p.s.i.	Time maximum pressure, milliseconds		Maximum pressure, p.s.i.	Time maximum pressure, milliseconds
1:1	78	250	1	73	210
1:1	84	210	2	78	200
1:1	80	230	3	78	210
1:1	78	220	4	76	210
1:1	81	190	5	76	190
1:1	81	230	6	77	210
1:1	1/92	150	7	1/95	180

1/ Oscillations.

Ignition position	1	2	3	4	5	6	7	Partition ratio 1:1
Distance to partition plate, in.	18	12	6	3	9-1/2	16	22-1/2	
Ignition position	1	2	3	4	5	6	7	Partition ratio 3:1
Distance to partition plate, in.	31	25	19	9-1/2	3	3	9-1/2	
Ignition position	1	2	3	4	5	6	7	Partition ratio 7:1
Distance to partition plate, in.	37-1/2	31-1/2	25-1/2	16	9-1/2	3	3	

DISCUSSION OF TEST DATA

Table A. Without an obstruction in the box, the pressure develops gradually to a maximum value for central ignition of 80 pounds per square inch in approximately 0.25 second. (See curves 1 to 3, fig. 2.)

Table B. With the 10-inch-diameter opening partition and a compartment ratio of 1:1, the effect of the partition increases with the distance from the partition to the point of ignition. (See curves 4 to 11, fig. 3.) The effect even with a 10 inch diameter opening in a 12-inch-square plate in producing turbulence of the gas is shown in the rapid rise in the pressure curve after an initial slow rise as in table A. Pressures are of the same magnitude as in table A, except when vibrations occur as shown by comparing curve 10 with curve 11, figure 3, when the pressure may differ by 20 to 30 pounds per square inch. Tests under apparently identical conditions frequently produce both types of curves, which differ only in the high-frequency oscillations superimposed on one curve. (Compare curves 56 and 57 and curves 58 and 59, fig. 2.) This behavior is similar to that of the critical conditions that must be met for resonance in general.

With the partition dividing the box in a 7:1 volume ratio, the effect of the partition is not as sudden or effective in causing a sharp break in the rise of the pressure curve. (See curves 4 to 25, figs. 3, 4, and 5.) It is interesting to observe that the shape of the two sets of curves shown in figures 4 and 5 is almost identical, since these were taken at the two opposite ends of the box. The largest pressures occur in the larger of the two compartments with ignition in this compartment. The largest pressure normally would be expected in the smaller compartment on the basis of pressure piling. The smallest pressure, by the same reasoning, would be expected to occur in the smaller compartment with ignition in this compartment, and this is actually the case. The difference in the pressures involved, as compared to those shown in table A for no partition plate, is about ±15 pounds per square inch.

Table C. With the 8-inch-diameter opening partition, the results are similar to those given in table B but more pronounced. Oscillations occur more frequently in the pressure curves. With a compartment ratio of 1:1, pressures

of 110 to 130 pounds per square inch were obtained with ignition at either extremity and measured at either end of the box. With both the compartment ratios of 3:1 or 7:1, the high pressures in the larger compartment are associated with a corresponding low pressure in the smaller compartment.

Table D. With the 4-inch-diameter opening partition, the general trend shown in tables B and C is continued. The effect of the smaller opening in producing a much more rapid and abrupt rise in pressure is shown. (See curves 26 to 47, figs. 6, 7, and 8.) The highest pressures are again obtained for a compartment ratio of 1 to 1 for ignition at the extremities of the box. High pressures also are obtained for a compartment ratio of 3:1 in the smaller compartment for ignition at the extremity of the larger compartment. The smallest pressures, as in the case for the 10-inch-and 8-inch-diameter partition plates, are obtained for the compartment ratio of 7:1. This would seem to indicate that the effect of pressure piling is negligible in these particular tests and that some other explanation must be sought, possibly in the dynamics of gases.

Table E. With the 2-inch-diameter opening and a compartment ratio of 1:1, very high pressures, about 300 pounds per square inch, were obtained. Again, maximum pressures are observed for ignition at either extremity of the box. Comparison of the curves 48 to 55, figure 9, shows the same general pattern, although the pressures vary from 91 pounds per square inch to 315 pounds per square inch. The higher-pressure curves only differ from the lower-pressure curves in that high frequency and large-amplitude vibrations appear in the first 30 milliseconds or so of the curve. The high pressures are those of a transitory and rapidly fluctuating nature, entirely different from that assumed as a result of the effect of pressure-piling. The oscillations are considerably greater than anything shown previously, which may be due to instrumentation. Curve 49, figure 9, shows the high-frequency oscillations more clearly than curve 48, figure 9, since the 10,000-cycle per second carrier frequency was eliminated by direct-current operation of the gage. The very rapid and high pressures are first made evident audibly by the shattering type of explosion usually associated with detonation by solid explosives.

CONCLUSION

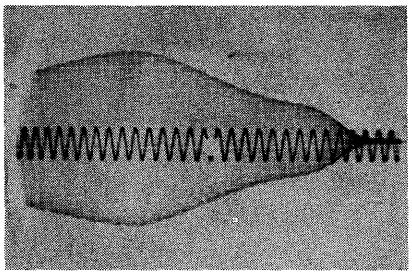
An attempt has been made in this report to predict and evaluate the effect of pressure piling in any given explosion-proof compartment on the basis of its geometry. As a beginning, a simple type of rectangular box that could be divided easily into separate compartments was employed. By extending these tests to more closely represent the more-complicated commercial enclosures taken with their contents, prediction of pressure piling should be made with greater confidence than possible at present.

With this in view, continuation of this investigation is planned. Higher-frequency gages will be used to insure greater reliability in the measurement of pressures. Possibility of cavity resonance should be eliminated by the use of flush-type diaphragms.

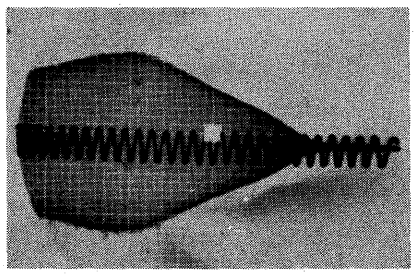
These general deductions are made on the basis of the test results:

DYNAMIC PRESSURE CURVES

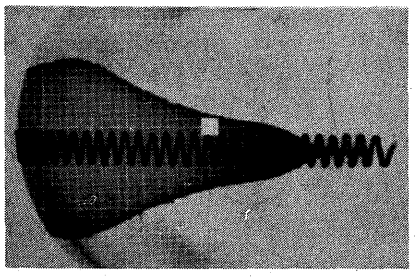
No Partition
Gage Position No. 1



(1) Ignition No. 1 - 74 p.s.i.

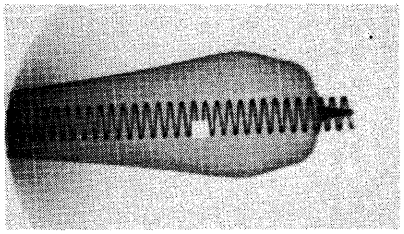


(2) Ignition No. 4 - 78 p.s.i.

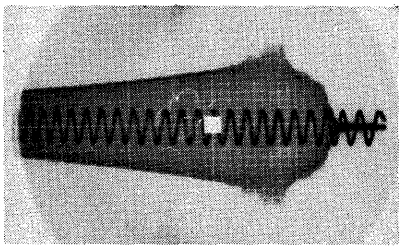


(3) Ignition No. 7 - 74 p.s.i.

Four-inch Diameter Opening
Partition Ratio 7 to 1
Gage Position No. 2

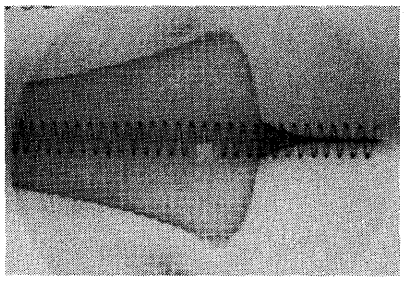


(56) Ignition No. 5 - 78 p.s.i.

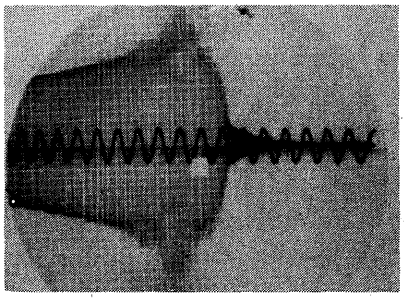


(57) Ignition No. 5 - 97 p.s.i.

Four-inch Square Opening
Partition Ratio 7 to 1
Gage Position No. 1



(58) Ignition No. 4 - 93 p.s.i.

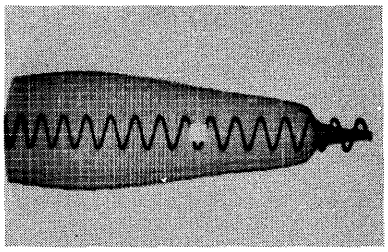


(59) Ignition No. 4 - 123 p.s.i.

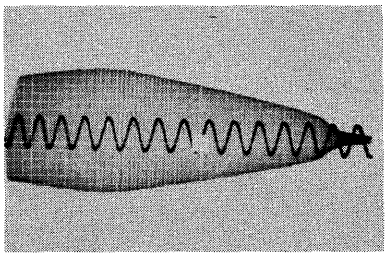
Figure 2. - Dynamic pressure curves.

DYNAMIC PRESSURE CURVES

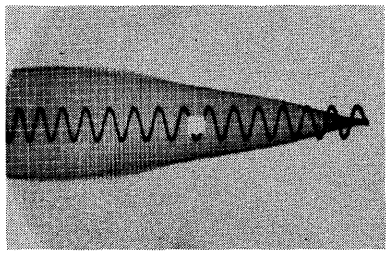
Ten-inch Diameter Opening
Partition Ratio 1 to 1
Gage Position No. 2



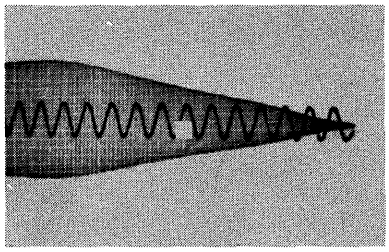
(4) Ignition No. 1 - 73 p.s.i.



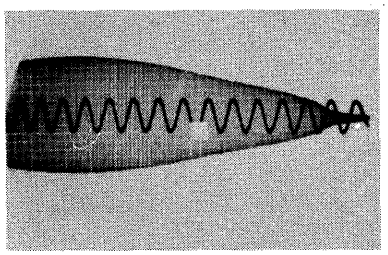
(5) Ignition No. 2 - 78 p.s.i.



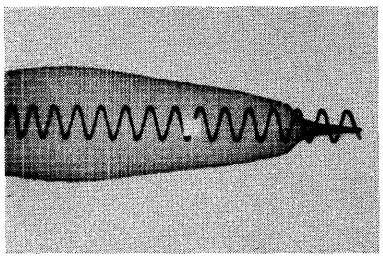
(6) Ignition No. 3 - 78 p.s.i.



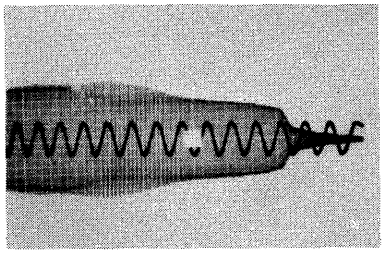
(7) Ignition No. 4 - 76 p.s.i.



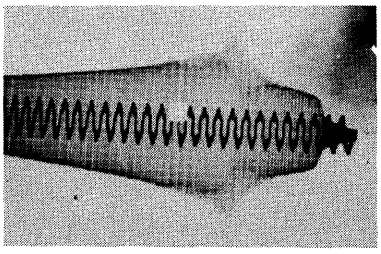
(8) Ignition No. 5 - 76 p.s.i.



(9) Ignition No. 6 - 77 p.s.i.



(10) Ignition No. 7 - 79 p.s.i.

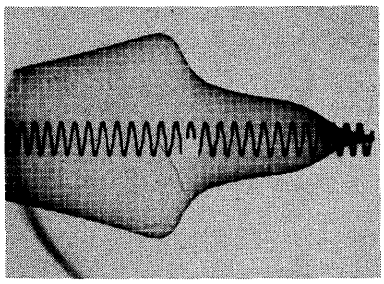


(11) Ignition No. 7 - 95 p.s.i.

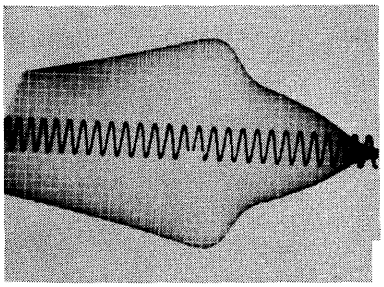
Figure 3. - Dynamic pressure curves.

DYNAMIC PRESSURE CURVES

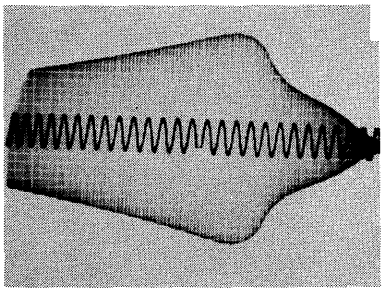
Ten-inch Diameter Opening
Partition Ratio 7 to 1
Gage Position No. 1



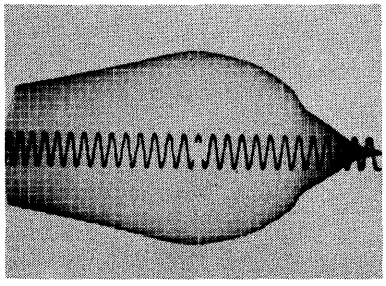
(12) Ignition No. 1 - 88 p.s.i.



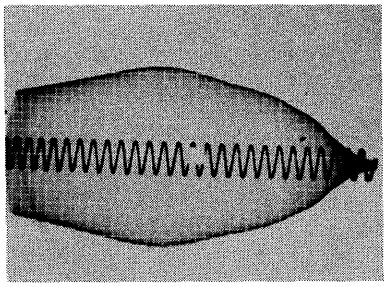
(13) Ignition No. 2 - 90 p.s.i.



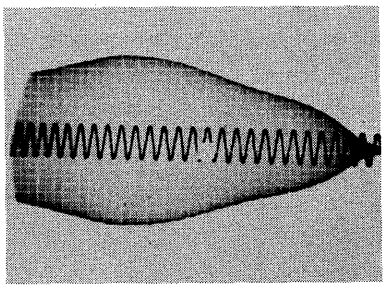
(14) Ignition No. 3 - 90 p.s.i.



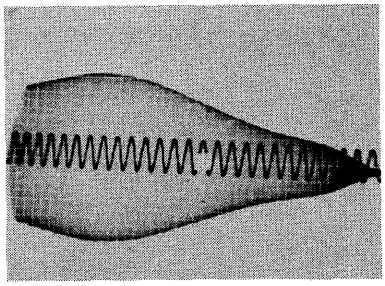
(15) Ignition No. 4 - 86 p.s.i.



(16) Ignition No. 5 - 78 p.s.i.



(17) Ignition No. 6 - 73 p.s.i.

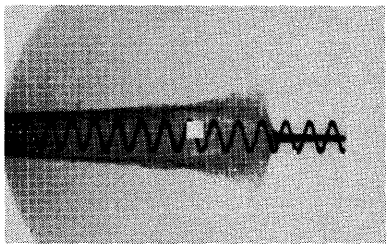


(18) Ignition No. 7 - 73 p.s.i.

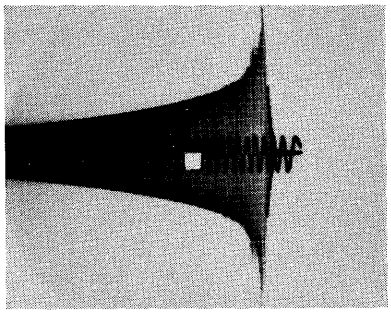
Figure 4. - Dynamic pressure curves.

DYNAMIC PRESSURE CURVES

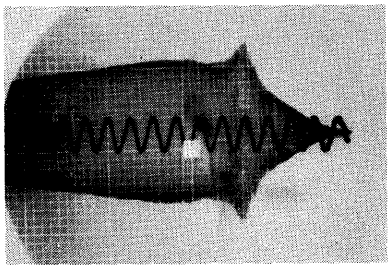
Four-inch Diameter Opening
Partition Ratio 1 to 1
Gage Position No. 2



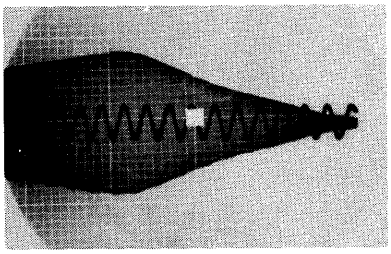
(26) Ignition No. 1 - 129 p.s.i.



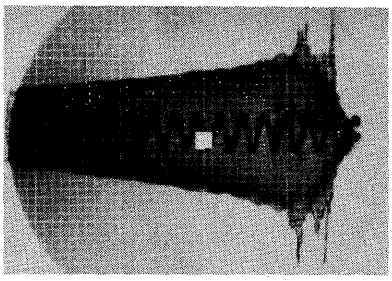
(27) Ignition No. 2 - 195 p.s.i.



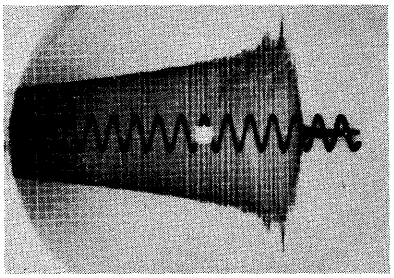
(28) Ignition No. 3 - 127 p.s.i.



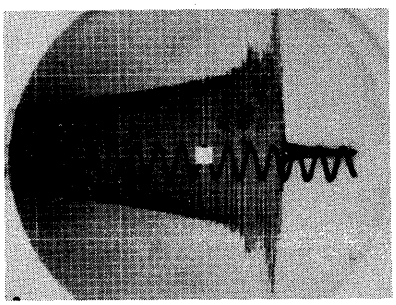
(29) Ignition No. 4 - 83 p.s.i.



(30) Ignition No. 5 - 156 p.s.i.



(31) Ignition No. 6 - 151 p.s.i.

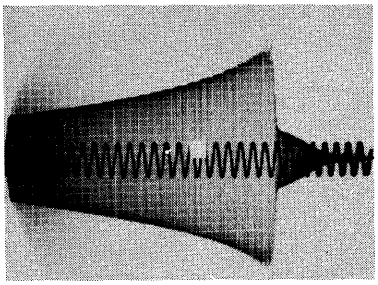


(32) Ignition No. 7 - 166 p.s.i.

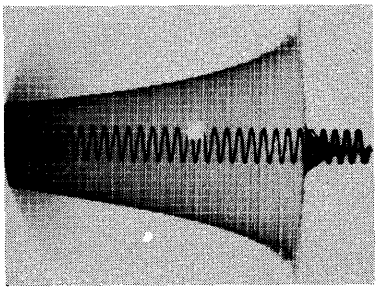
Figure 6. - Dynamic pressure curves.

DYNAMIC PRESSURE CURVES

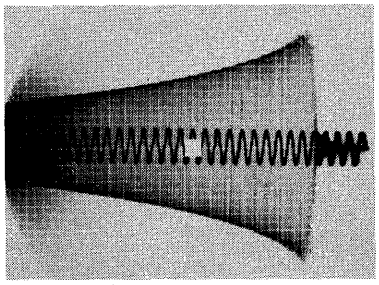
Four-inch Diameter Opening
Partition Ratio 3 to 1
Gage Position No. 1



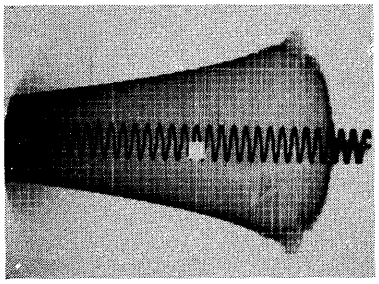
(33) Ignition No. 1 - 106 p.s.i.



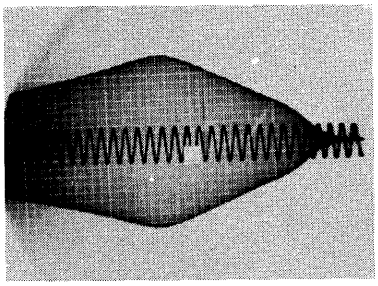
(34) Ignition No. 2 - 113 p.s.i.



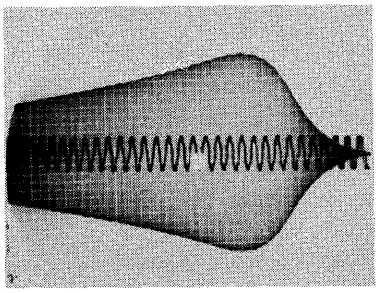
(35) Ignition No. 3 - 102 p.s.i.



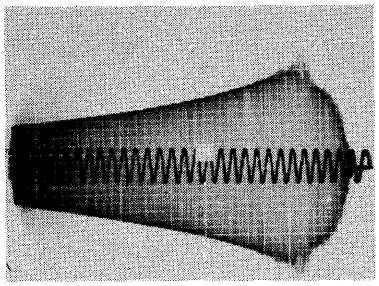
(36) Ignition No. 4 - 92 p.s.i.



(37) Ignition No. 5 - 74 p.s.i.



(38) Ignition No. 6 - 85 p.s.i.

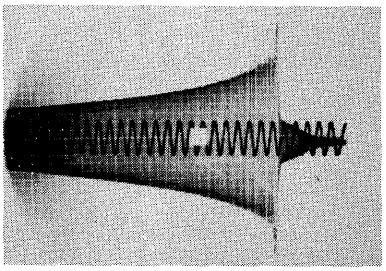


(39) Ignition No. 7 - 96 p.s.i.

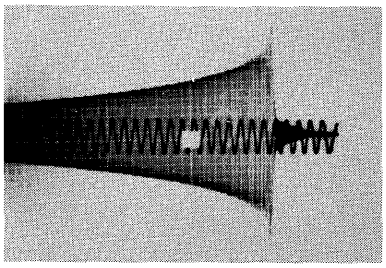
Figure 7. - Dynamic pressure curves.

DYNAMIC PRESSURE CURVES

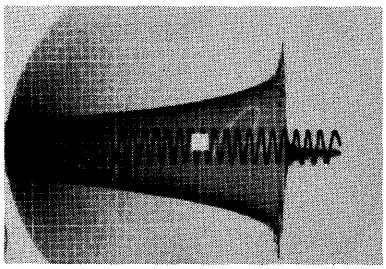
Four-inch Diameter Opening
Partition Ratio 3 to 1
Gage Position No. 2



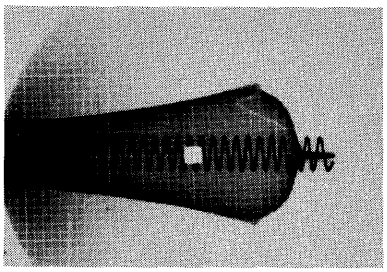
(40) Ignition No. 1 - 146 p.s.i.



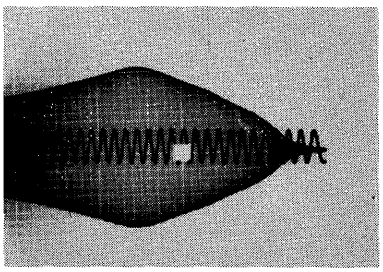
(41) Ignition No. 2 - 135 p.s.i.



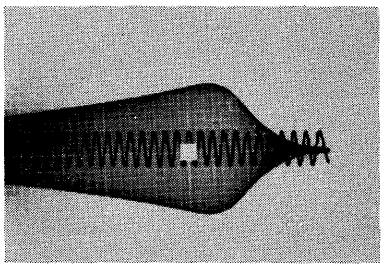
(42) Ignition No. 3 - 130 p.s.i.



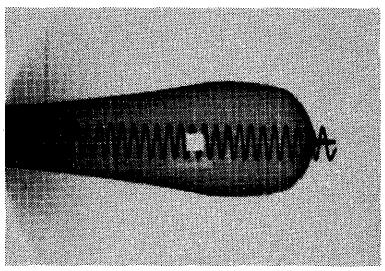
(43) Ignition No. 4 - 92 p.s.i.



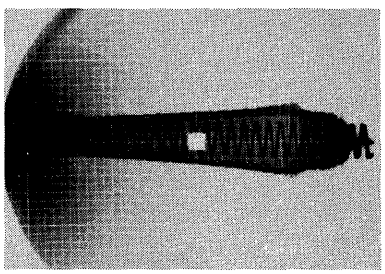
(44) Ignition No. 5 - 71 p.s.i.



(45) Ignition No. 6 - 78 p.s.i.



(46) Ignition No. 7 - 68 p.s.i.

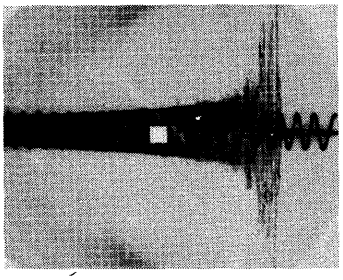


(47) Ignition No. 7 - 86 p.s.i.

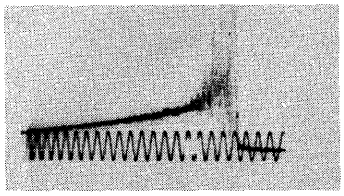
Figure 8. - Dynamic pressure curves.

DYNAMIC PRESSURE CURVES

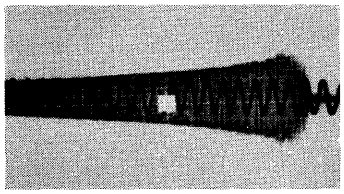
Two-inch Diameter Opening
Partition Ratio 1 to 1
Gage Position No. 2



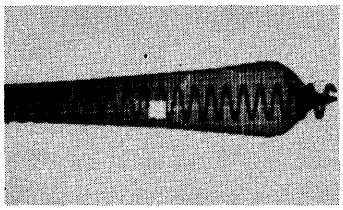
(48) Ignition No. 1 - 315 p.s.i.



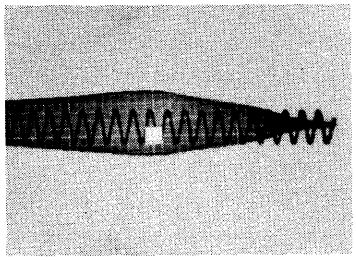
(49) Ignition No. 1 - 300 p.s.i.



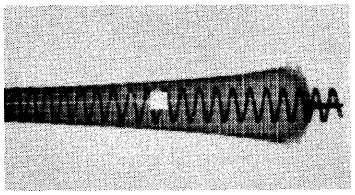
(50) Ignition No. 2 - 115 p.s.i.



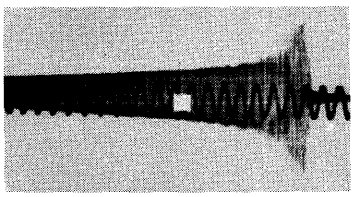
(51) Ignition No. 3 - 91 p.s.i.



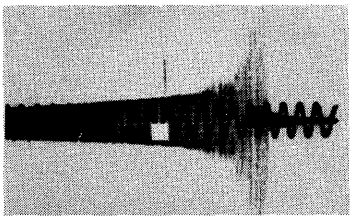
(52) Ignition No. 4 - 85 p.s.i.



(53) Ignition No. 5 - 96 p.s.i.



(54) Ignition No. 6 - 178 p.s.i.



(55) Ignition No. 7 - 234 p.s.i.

Figure 9. - Dynamic pressure curves.

1. Pressures of about 125 pounds per square inch are obtainable with openings as large as 8 inches in diameter in a 12-inch-square plate. These pressures are due mainly to high-frequency vibrations. The 50-percent safety margin sometimes provided in commercial enclosures may be reached under these conditions.

2. There is a critical ratio between the size of the hole in the partition plate and the distance of the ignition point from the plate before a vibratory type of explosion can be generated. It would be of considerable interest to determine the extent to which this ratio is independent of the size of the box.

3. Pressure gages, such as those specially designed for detonation studies[7] in gasoline engines, whould be used in future explosion tests to insure adequate high-frequency response. A frequency response at least 10 times greater than that of the present gages would be desirable. This need is also indicated from the recent tests by Titman and Haig[8] and Staples.[9]

7/ Titman, H., Measurement of Dynamic Pressures: Safety in Mines Research Establishment Rep. 12, November 1950, 31 pp.

8/ Titman, H., and Haig, J., Pressure Generated During Explosion of a Pentane-Air Mixture Inside a Core-Cooled Motor: Safety in Mines Research Establishment, part I, Rept. 11, July 1950, 19 pp.

9/ Staples, H., Pressure Generated During Explosion of a Pentane-Air Mixture Inside a Core-Cooled Motor: Safety in Mines Research Establishment, part II, Rept. 27, June 1951, 17 pp.