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Gaseous Explosions

VI—Flame and Pressure Propagation[1]

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This investigation was undertaken in order to obtain experimental data concerning the relation between flame propagation and the pressure changes resulting therefrom. The apparatus used and its method of operation are described in detail and the experimental data are interpreted and discussed.

ALTHOUGH many investigators have photographed the movement of the flame in gaseous explosions, and some have recorded the rise in pressure at one point in the explosion chamber while photographing the flame, practically all conclusions concerning the pressure effects accompanying the flame are entirely speculative, as no experimental data have been reported giving the pressures developed by and accompanying the flame as it progresses through the explosive mixture.

Many investigators have observed a halt in the advance of the flame front as it progresses through the explosive mixture. The cause of this halt has been explained in various manners. Dixon[2] believes it to be due to a reflected pressure wave set up by the igniting spark and traveling through the unburned gases ahead of the flame. After being reflected from the far end of the explosion chamber it meets the flame front before the flame front reaches the end of the explosion chamber.

[1] Part of a thesis submitted by J. V. Hunn in partial fulfilment of the requirements for the degree of doctor of philosophy in the University of Michigan.

[2] *J. Soc. Automotive Eng.*, **9**, 237 (1921).

Woodbury, Lewis, and Canby[3] observed this halt in the flame front when photographing the flame and recording the pressures developed at the end of the explosion chamber opposite the point of ignition, and explained it in the following manner:

> It has been previously shown that the flame front is pushed forward by the expansion of the burned gases and that the unburned gases are compressed to a high density at the same time. Obviously a point can be reached at which the pressure due to the temperature behind the flame is equaled by the pressure due to the density ahead of the flame. At that point the flame front is no longer pushed forward; the propagation is arrested.

Midgley[4] and Janeway developed mathematical treatment of progressive flame travel up to the detonation wave based on the assumption that the pressure ahead of the flame must be greater than the pressure behind the flame in order to supply the energy required to push the unburned gas into the flame and give the particles behind the flame their velocity to the rear of the flame front. They furnish no experimental evidence to support this assumption.

Apparatus

The apparatus may be divided into four major parts: (1) the bomb and assembly, (2) the pressure recorder, (3) the flame recorder, and (4) the wiring and timing mechanism.

Bomb and Assembly—The bomb was made from a special steel casting, 114.3 cm. (45 inches) long and 15.2 cm. (6 inches) square with a 7.62-cm. (3-inch) diameter cylindrical hole cast lengthwise through the center. The casting was cut off 12.7 cm. (5 inches) from each end to insure sound metal. This left 88.8 cm. (35 inches) over-all as the length of the bomb casting.

A circular tongue, 7.62 cm. (3 inches) i. d. and 10.1 cm. (4 inches) o. d. at the base and 8.9 cm. (3.5 inches) o. d. at the top, was turned on each end of the bomb as shown in Figure 3. The ends of the bomb were closed with a cast-iron plate 15.2 cm. (6 inches) square and 3.8 cm. (1.5 inches) thick grooved to fit the tongue on the ends of the bomb and held in place by four heavy cap screws. A rubber gasket was placed in the bottom of the groove in the cast-iron plate to make the joint gas-tight.

A slot 1.27 cm. (0.5 inch) wide was cut lengthwise through the bomb on one side to act as a window for photographing the flame. Three bridges 1.27 cm. (0.5 inch) wide and a bridge at each end 2.54 cm. (1 inch) wide were left across the slot for strengthening and gasket supports. This slot was covered with two plate-glass windows 5.1 cm. (2 inches) wide, 0.63 cm. (0.25 inch) thick, and 43.2 cm. (17 inches) long set into a recess cut in the bomb over the slot. A rubber gasket was placed between the glass and the metal of the bomb. Two bars of steel 86.3 cm. (34 inches) long, 1.9 cm. (0.75 inch)

[3] *Ibid.*, **9**, 209 (1921).

[4] *J. Soc. Automotive Eng.*, **10**, 357 (1922).

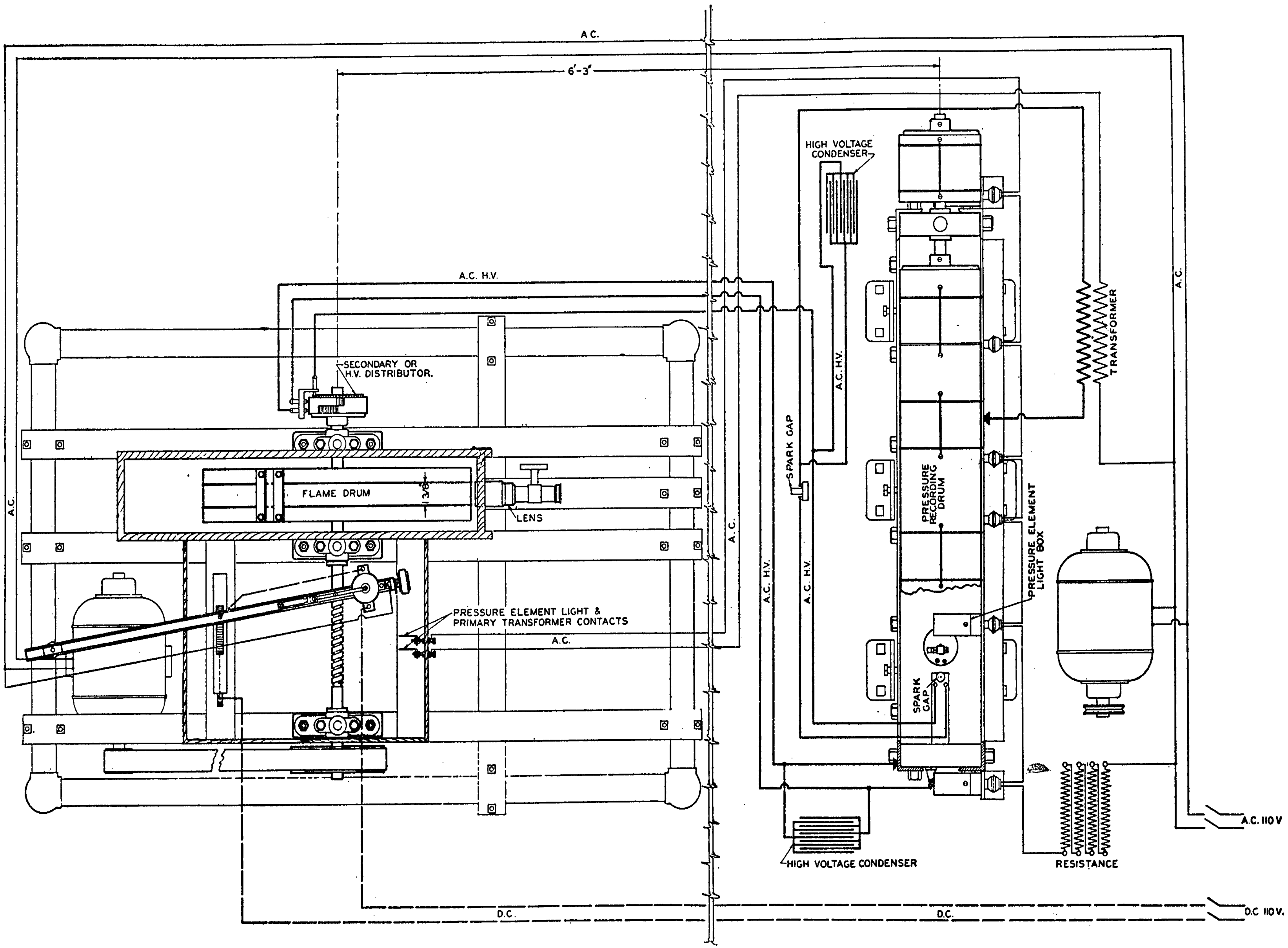


Figure 1—Assembly and Wiring Diagram

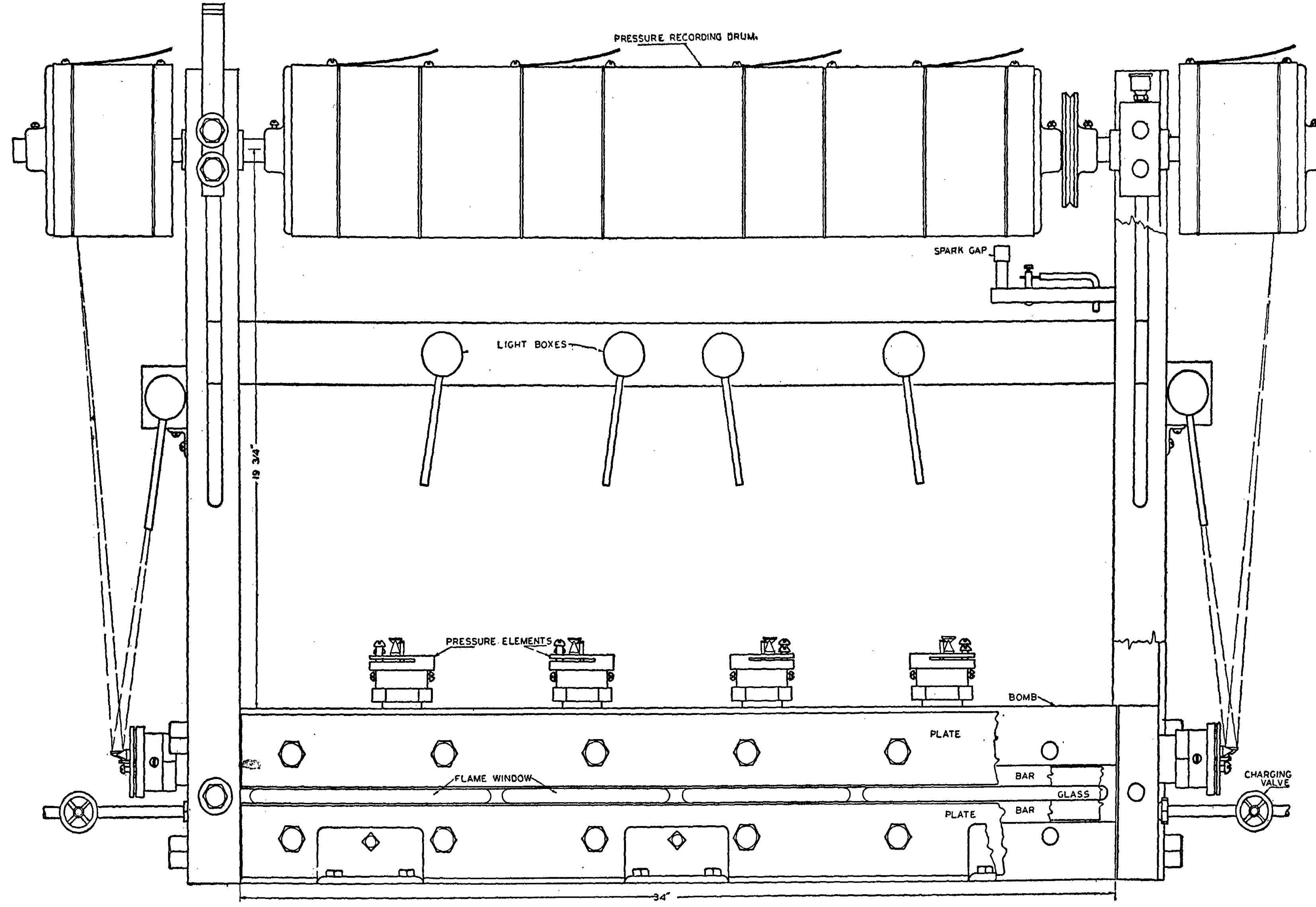


Figure 2—Bomb and Pressure Recorder

wide, and 1.27 cm. (0.5 inch) thick were placed on top of the glass, but separated from it by a rubber gasket, along each side of the window recess. These bars projected about 0.32 cm. (0.125 inch) above the face of the bomb and were held in place by two other bars of the same length, 6.4 cm. (2.5 inches) wide and 0.63 cm. (0.25 inch) thick, which were fastened to the bomb by means of cap screws. This arrangement, as shown in Figures 2 and 3, was necessary in order that an even pressure might be brought to bear on the window to make it gas-tight without breaking the glass.

The bomb was constructed to accommodate six pressure elements, one on each end and four equally spaced along the top side adjacent to the flame window, as shown in Figures 2 and 3. Details of the pressure elements will be taken up in conjunction with the pressure recorder.

Two holes were also drilled through each end plate and tapped with 1.27-cm. (0.5-inch) pipe threads for spark plugs and charging valves.

PRESSURE-RECORDING APPARATUS—The time-pressure cards were obtained photographically by deflecting a pencil of light by means of a movable concave mirror mounted on the pressure elements and brought to a focus on a revolving drum.

Lighting. The light was obtained from a 6–8 volt, 50-c. p., double-contact auto-headlight bulb overloaded to 12 volts. Each bulb was enclosed in an individual light box shown in detail in Figure 7 and shown in position in Figures 2 and 3. The light boxes were constructed so that the small beams of light coming from the shielding tubes could be individually adjusted to fall upon and just cover the mirrors of their respective pressure elements.

The four light boxes, furnishing light for the four pressure elements on the side of the bomb, were mounted by means of two screws each, to a 5.1-cm. (2-inch) angle iron, which in turn was supported by two of the 5.1-cm. (2-inch) angle-iron brackets holding the revolving drum. The angle iron could be raised or lowered for focusing the light, as reflected from the concave mirror, to a point upon the revolving drum. The light boxes for the two end pressure elements were mounted separately so that they might be focused individually. The distance from the mirror to the revolving drum is greater in the case of the end pressure elements and therefore requires separate adjustment of the light boxes.

Pressure Elements. The pressure elements were of the diaphragm type and so designed as to have minimum weight and movement to the moving parts, in order to reduce the lag of the indicator, due to the inertia of the moving parts, to as small a time interval as possible.

The pressure-element body was made from 5.7-cm. (2.25-inch) hex bar cold-rolled steel. (Figure 5) The pressure-element head was made from 6.4-cm. (2.5-inch) round bar cold-rolled steel.

The pressure-element head fitted down over the top of the element body and was held in place by two lock screws, pressing against the friction blocks, in the side of the element body. This arrangement allowed the element head to be rotated in either direction, so that the light could be adjusted to fall on the axis of the revolving drum, and locked in any position without raising or lowering the element head. To raise or lower the element head would throw the light out of focus.

A corrugated brass diaphragm 3.8 cm. (1.5 inches) in diameter and 0.508 mm. (0.020 inch) thick covered the bottom of the element body and was held rigidly in place when the element was screwed into the bomb. The diaphragm had an effective diameter of 2.54 cm. (1 inch). A lead gasket was placed between the diaphragm and the bottom of the element recess in the bomb. This arrangement effectively sealed the element opening.

Diaphragms of different material and thickness were tried until one was obtained that would give the maximum deflection for the pressures developed without permanent deformation. The diaphragm used would withstand 7.03 kg. per sq. cm. (100 pounds per square inch) without taking a permanent set.

The motion of the diaphragm was transmitted to a steel rod 9.5 cm. ($3^3/_4$ inches) long and 2.38 mm. ($^3/_{32}$ inch) diameter which passed through a hole in the center of the diaphragm. The part of the rod passing through the diaphragm was threaded and a small brass nut on each side of the diaphragm allowed the rod to be fastened rigidly to it. The rod passed up through the center of the element body and through the center of the element head, guided at the bottom of the body and at the top of the head. Around the top of the rod was a narrow groove into which fitted the small brass wing, V-notched, projecting from the bottom of the mirror mounting. This method of connecting the rod to the mirror mounting proved very satisfactory as it allowed a small change of angle of the wing with the rod without any play or lost motion at the joint. In this way the longitudinal movement of the rod was transmitted as angular rotation to the mirror mounting and thence to the mirror.

The mirror mounting was made of sheet brass 0.381 mm. (0.015 inch) thick. A small steel rod 1.59 mm. (0.067 inch) in diameter pointed at both ends was soldered to the bottom of the mirror support and served as the axis. The mirror mounting was held in place by the steel spring as shown in Figure 5. The mirror was held in the mounting by small strips of brass, which were part of the mounting, and projected above the mirror at each corner and were bent down over it.

The mirrors were glass 1.27 cm. (0.5 inch) square, 1.59 mm. (0.067 inch) thick, with the concave side having a radius of curvature of 33 cm. (13 inches).

Silvering Mirrors. The silvering of the mirror offered a considerable problem, as it was desirable that the reflecting side should be the same as that upon which the silver was deposited. This was necessary so that there would be no dispersion of light due to refraction, which would be the case if the light passed through the glass. The silver deposited by ordinary methods was thin and soft and would not long adhere to the glass without lacquering. Small ripples in the lacquer coat interfered with the focusing of the light and gave a corona effect around the central point of light, which registered on the photograph as a line with blurred edges.

These difficulties were overcome by silvering the glass by a special procedure. The ordinary silvering solutions were used but applied to the glass in the following manner: The glass was first cleaned in caustic solution and then in nitric acid, then rinsed in distilled water and rubbed with a chamois dipped in alcohol. While the glass was still wet the silvering solution was sprayed upon it, with considerable force, by an air jet. The silver nitrate and reducing solutions were allowed to mix and the reaction start before they entered the jet.

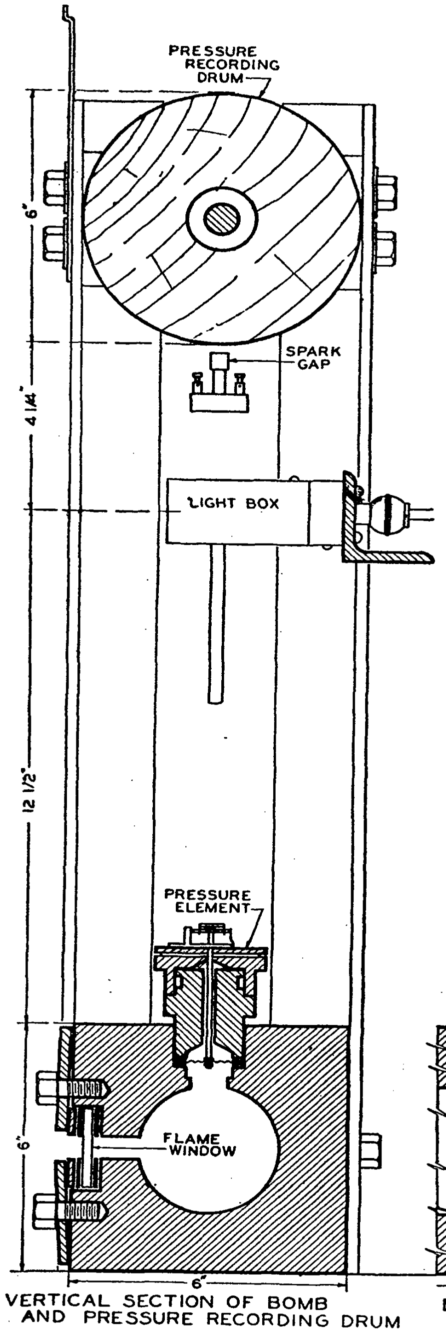
In this way a hard, dense, and very adherent silver deposit of any desired thickness could be built up upon the glass. This deposit required no protecting coat of any kind, for as it oxidized on the surface it could be repolished with fine jeweler's rouge.

Pressure-Recording Drum. The revolving drum for carrying the photographic recording paper was made of solid ply maple 15 cm. (6 inches) in diameter and mounted as shown in Figure 2. Wires 2 inches apart were drawn around the drum in grooves to hold them in place. These wires served as guides for the recorder paper. The paper was held to the drum by means of spring wire clips sunk in a groove cut parallel with the axis of the drum. The lights of the pressure elements were so adjusted that they all fell upon a line parallel with the axis of the drum. The grooves, containing the recorder paper clips, were used for this purpose.

The drum was driven by a $^{1}/_{4}$-horsepower electric motor, mounted upon the floor to reduce vibration. The power was transmitted by a 0.63-cm. (0.25-inch) round leather belt to a jack shaft and from there to the drum.

FLAME RECORDER—The flame travel was recorded photographically upon panchromatic film by means of a rapid lens.

Flame-Recording Drum. The flame drum (Figures 1 and 4) for carrying the motion-picture film was made from a cast-iron belt pulley, 50.8 cm. (20 inches) in diameter and with a 10.1-cm. (4-inch) face, mounted upon a pipe frame entirely separate from the bomb. The pipe frame was securely braced with heavy angle iron and fastened to the concrete floor in eight places with 1.27-cm. (0.5-inch) expansion bolts.



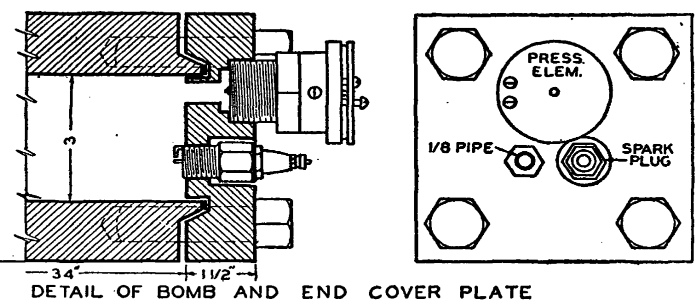


Figure 3

The face of the flame drum was ground, after it was mounted into position, until it was true with its axis of rotation within 0.0127 mm. (0.0005 inch) when turning at 700 r. p. m. This accuracy was necessary so that the photographic film would not be carried out of focus with the lens. Two grooves 3.5 cm. (0.38 inch) apart were cut in the face of the flame drum. Wires were drawn around the drum, held in position by the grooves, which served as guides in placing the film on the drum. Two brass clips, which were clamped down by coiled springs below the face of the drum, held the film in position on the drum. The drum was very carefully balanced until no vibration was perceptible, as this vibration would affect the flame photograph.

Lens. An Ultrastigmat lens F:1.9, in a micrometer mount, was mounted in front of the flame drum as shown in Figures 1 and 4. A rack and pinion at the bottom of the lens mountng was used for the coarse focusing of the lens. The micrometer mount was used for the fine focusing of the lens.

The flame drum was entirely shielded by a wooden and metal box with a hinged top to allow access for placing and removing the film. The focusing was done by means of a small hole through the shield which allowed a view of the surface of the drum in back of the lens. This hole was covered by a slide of sheet metal.

The shaft of the flame drum was supported by three heavy block bearings (Figure 1) and driven by means of a flat belt from a $^1/_4$-horsepower motor mounted on the floor.

WIRING AND TIMING MECHANISM—High-voltage spark gaps, fed from a small transformer, were used to establish time intervals and time relations between the pressure drum and the flame drum. The same transformer was also used for firing the charge in the bomb. The transformer was supplied with 60-cycle alternating current.

The high-voltage output of the transformer would jump the gaps only when a sufficiently high voltage had been reached to break down the resistance of the gaps. This, of course, would occur when the voltage was rising or at its peak, depending upon the width of the gaps, or with a frequency of 120 per second when 60-cycle current was used. Therefore, when this spark was photographed on moving film and paper it registered a dot or group of dots every $^1/_{120}$ of a second.

Where two spark gaps are connected in series, one placed so as to register on one film traveling at one speed and the other to register on another film traveling at a different speed, the time relations between the two films is definitely established, because the sparks jump both gaps at the same instant, neglecting of course the extremely small interval required for the travel of the electricity from one gap to the other.

The type of spark gap used is shown in detail in Figure 6. The spark jumps between the end of the wire and the inner edge of the tube. The gaps are mounted on blocks of Bakelite. The tube arrangement prevents fogging of the film and paper by diffusion of the light from the spark.

One spark gap was mounted directly below the pressure drum and fastened to the angle irons supporting the drum. The light from this gap was registered on the same photograph as the pressure from the pressure element below it. (Figures 1, 2, and 3) The other spark gap was mounted in front of and at the center of the flame window and faced the photographic lens so as to register on the flame photograph. (Figure 1)

This position of the gap brought it directly in front of one of the bridges across the flame window. The bridge across the window shut off the light of the flame at this point and therefore made the photograph of the spark easily discernible.

Because of the high voltage used, the capacity effects of the bomb and wiring were great enough to cause sparks to jump across the gaps when one side of the secondary transformer circuit was open and only the primary closed. A condenser of sufficient capacity to absorb this discharge was placed across both gaps. The condenser also absorbed and stored energy while the voltage was building up in the transformer and lengthened the time necessary for the voltage to reach a sufficiently high potential for jumping the gap. When the resistance of the gap was broken down, high-frequency oscillating currents in the condenser circuit rapidly dissipated the energy of the charge, so that there would be

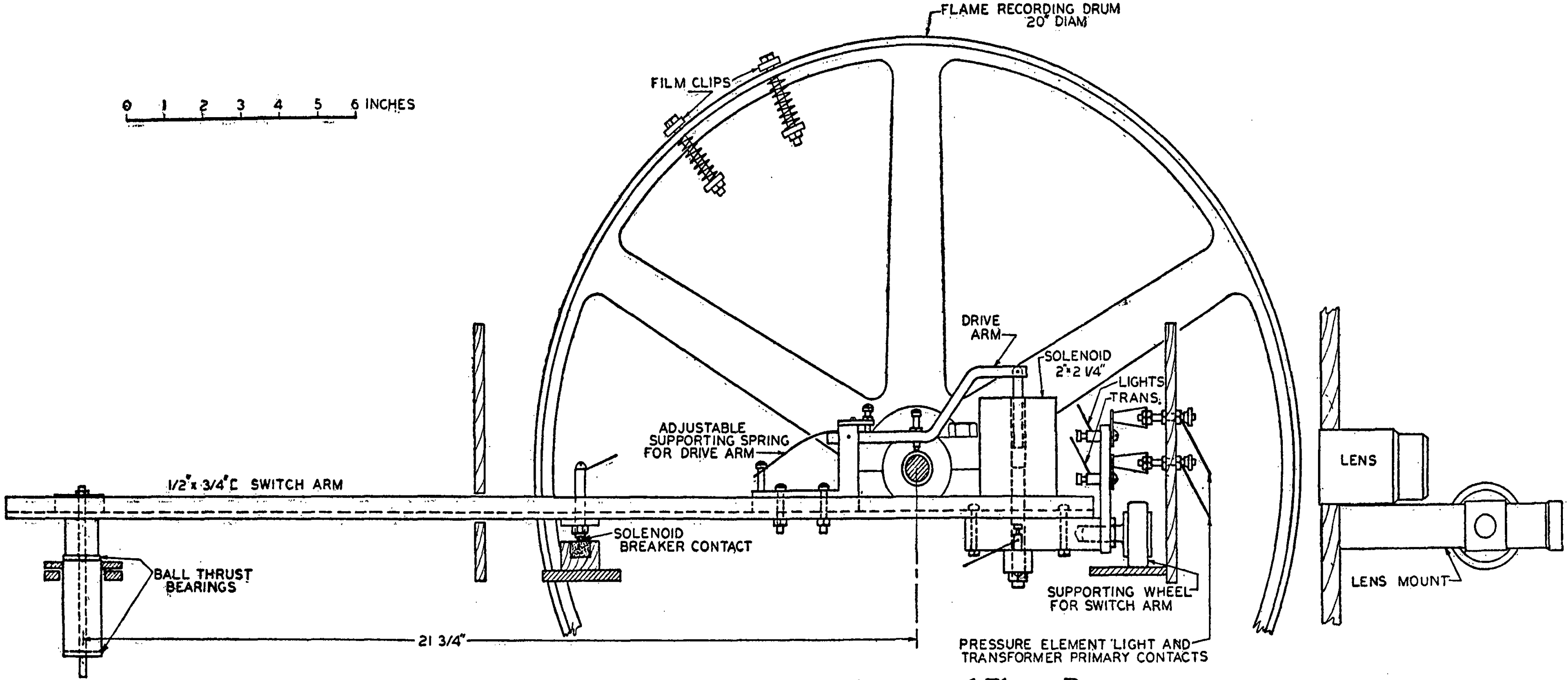


Figure 4—Detail of Automatic Switch Arm and Flame Drum

fewer but more intense discharges between each change in direction of the current in the transformer circuit.

A very effective condenser was made from glass tubing and mercury. A 3-mm. glass tube 60.8 cm. (24 inches) long, sealed at one end, was placed inside a 7-mm. glass tube 55.8 cm. (22 inches) long also sealed on one end. The 3-mm. tube and the annular space between the two tubes were filled with mercury. The two columns of mercury acted as two plates of a condenser. Units of this type were added

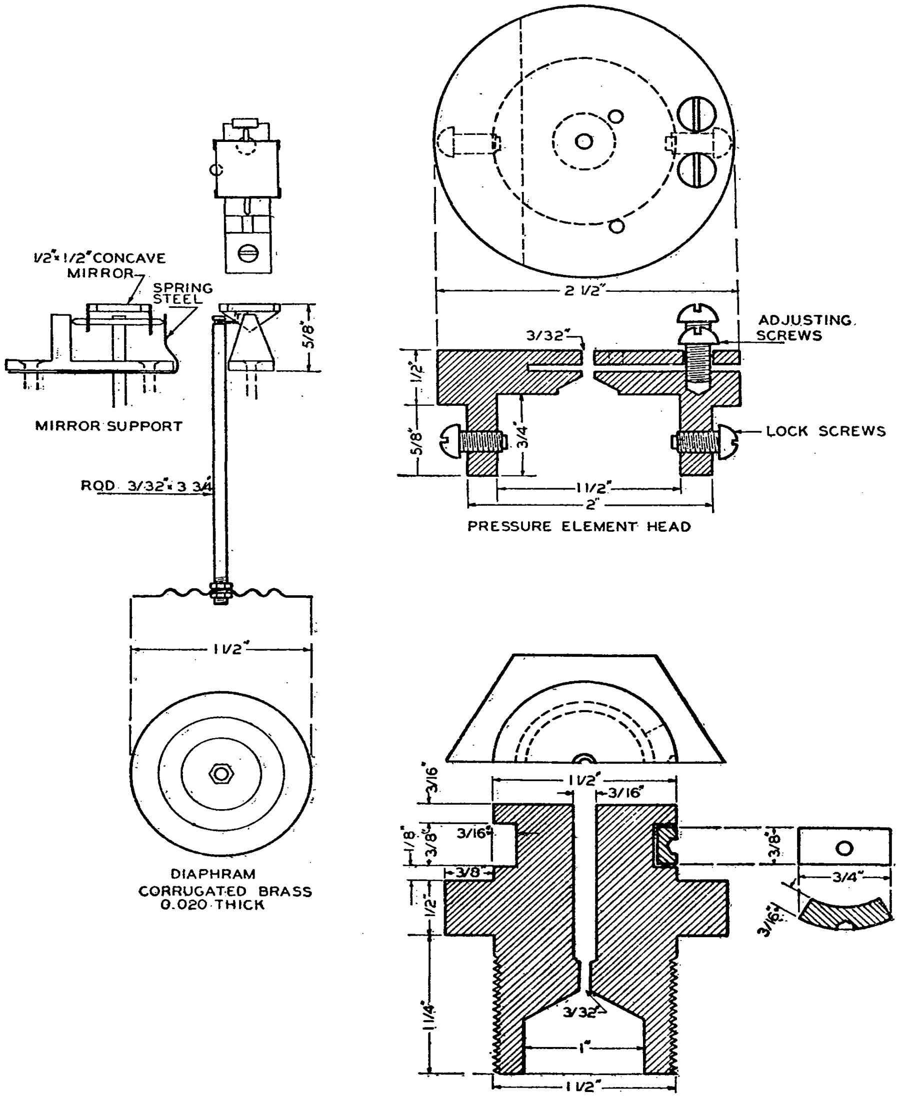


Figure 5—Detail of Pressure Element

until the condenser had the desired capacity. The advantage of this condenser lay in its ease of construction, replacement when punctured, and adjustment of capacity.

The rest of the firing and timing mechanism may best be described by following through the wiring diagram as shown by Figure 1. By closing the switch of the 110-volt a. c. line (lower right-hand corner of Figure 1) the motors driving the two drums are started and the voltage is also applied to one side of the pressure-element light circuit, through a resistance to control the voltage, and to one side of the primary winding of the transformer. The other lead to the lights and transformer terminates in two small brass contact plates at the end of the automatic switch arm.

After the drums are up to speed, the 110-volt d. c. switch (also in lower right-hand corner of Figure 1) is closed, which actuates the solenoid mounted on the switch arm. The details of construction of the switch arm are shown in Figure 4. The solenoid pulls a pin into a screw which is cut in the shaft of the flame drum. This screw, with a pitch of two threads per inch, carries the switch arm across the light and primary transformer contacts. Contact is first made with the light circuit. The primary transformer contact is closed when sufficient time has elapsed for the lights to attain full intensity.

One side of the secondary winding of the transformer is grounded to the bomb. The other side leads first through the two-timing gaps and then to the ring of the high-voltage distributor which is mounted on the end of the shaft of the flame drum. The shaft, turning clockwise, brings the small segment on the face of the distributor into contact with the outside brush shortly after the primary circuit of the transformer is closed. When the small segment of the distributor comes in contact with the outside brush, the secondary circuit of the transformer is closed through the spark plug and the charge in the bomb is fired. A condenser, similar to the one previously described, was placed across the spark-plug gap to prevent the firing of the charge by capacity discharge. The small segment of the distributor remains in contact with the brush a little over $^1/_{120}$ second. Therefore, the size of the segment depends on the speed of the flame drum. When the outside segment leaves the outside brush, the inside segment comes in contact with the inside brush. The line from the inside brush is grounded directly to the bomb. In this way the spark plug is shorted after one or possibly two discharges across the gap. This arrangement was used so that additional impulses would not be added to the burning mixture by additional sparks jumping the gap in the spark plug. The inner segment of the distributor was of such length that the total time required for the passage of both segments under both brushes would be slightly less than the time required for one revolution of the pressure drum. In this way overlapping of the timing dots on the pressure cards was avoided.

By the time that the inside segment of the distributor has left the inside brush, the light and primary transformer contacts have passed across the plates on the end of the switch arm, thus turning off the lights and breaking the primary circuit of the transformer. The switch arm continues to move until the d. c. circuit, actuating the solenoid, is broken by the brush which is carried on the switch arm, passing off of the switch block mounted beneath the switch arm.

Operation

After the bomb chamber was thoroughly flushed with oxygen, the fuel was measured into the charging valve by means of a pipet, and blown into the bomb with oxygen. Initial pressure was atmospheric.

Fuel Used—Carbon disulfide was the fuel used for the preliminary work. This compound, on burning, gave a bright luminous flame which was easily photographed. For each charge 0.71 cc. of carbon disulfide liquid, equivalent to 262 cc. of vapor, was used. If air instead of oxygen had been used, this size charge would have made a theoretical mixture.

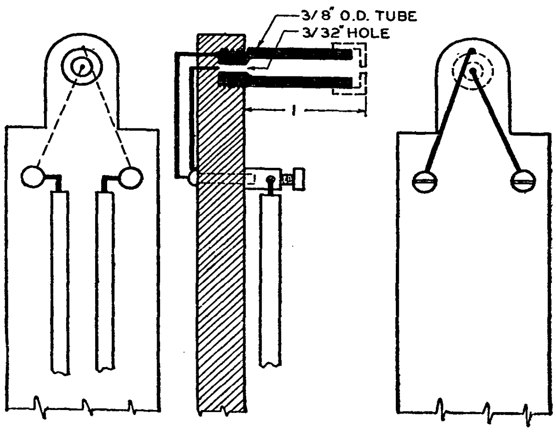


Figure 6—Detail of Spark Gap

Pressure-Recording Paper—The photographic paper was next placed in position upon the pressure drum. The paper used for this purpose was Recorder No. 1, furnished by the Eastman Kodak Company. The paper was cut into strips 7.62 cm. (3 inches) wide and 50.8 cm. (20 inches) long. This length allowed lapping on the drum so that a continuous photograph would result.

Flame-Recording Film—The photographic film was next fastened to the flame drum. Standard unperforated panchromatic motion-picture film was used for this purpose. This was cut into lengths 152.4 cm. (60 inches) long and had small tabs of canvas cemented to the ends. The teeth on the bottom of the film clips were able to obtain a better grip upon the canvas than they could upon the film itself. In this way the film could be drawn more tightly about the flame drum. If the film was not tight, the centrifugal action of the drum would throw the film away from the surface of the drum and so out of focus with the lens.

Safe Lights—It was of extreme importance to observe the correct manipulation of the dark-room safe lights. This necessity arose because the recorder paper was sensitive to green light but not sensitive to red, while in the case of the panchromatic film the conditions were reversed. Thus the same light could not be used for both the film and paper. By placing the recorder paper first and then shielding the pressure drum with a canvas curtain while the panchromatic film was being placed on the flame drum, this difficulty was overcome.

Exploding the Mixture—The apparatus was now ready for operation. This part of the procedure was very simple. The apparatus was so designed that the personal element was practically eliminated from the operation. The a. c. switch was first closed and the drums allowed to come up to speed, then the d. c. switch was closed. After the explosion, and after the pressure-element lights had gone out, the a. c. and d. c. switches were again opened and the operation was completed.

Developing the Photographic Records—The same precaution as to lights was observed while developing the paper and film. The paper was developed by nepara solution and the film by hydroquinone. The complete operation, including the developing after the paper and film were cut, required about one-half hour.

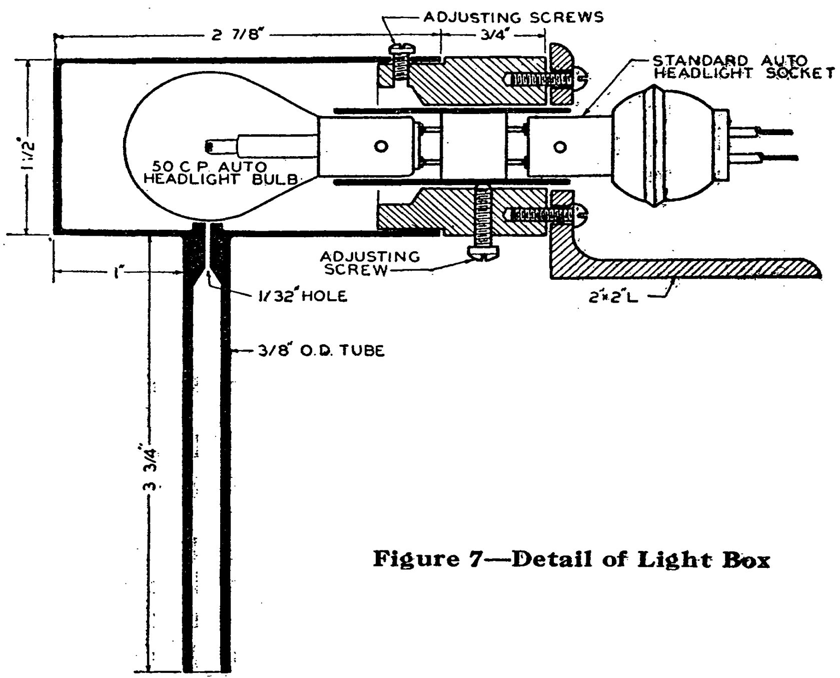


Figure 7—Detail of Light Box

After drying, the photograph of the flame was enlarged to such an extent that its time axis was the same as that of the time-pressure cards. This was accomplished by enlarging until the timing dots made by the electric spark on the flame photograph could be superimposed upon the timing dots on the time-pressure cards and exactly coincide. In this way the time relation between the photographs taken upon the two drums traveling at different speeds was definitely established.

Results

Interpretation of Data—The results of two check explosions so obtained are shown by Plates I and II. The lower photograph of each plate is the enlarged photograph of the flame. The time axis is horizontal and the vertical axis represents the length of the bomb. The three wide black horizontal lines through the photograph were made by the bridges across the window, shutting off the light of the flame at these points. The four narrow black horizontal lines marked A, B, C, and D show the positions occupied by the four pressure elements along the side of the bomb.

The four time-pressure curves above the flame photograph, marked A, B, C, and D, are reproductions of the four time-pressure cards taken along the sides of the bomb in the positions above indicated. The end-pressure elements were not used, as this investigation was primarily concerned with the pressures developed by the flame as it is propagated through the explosive mixture.

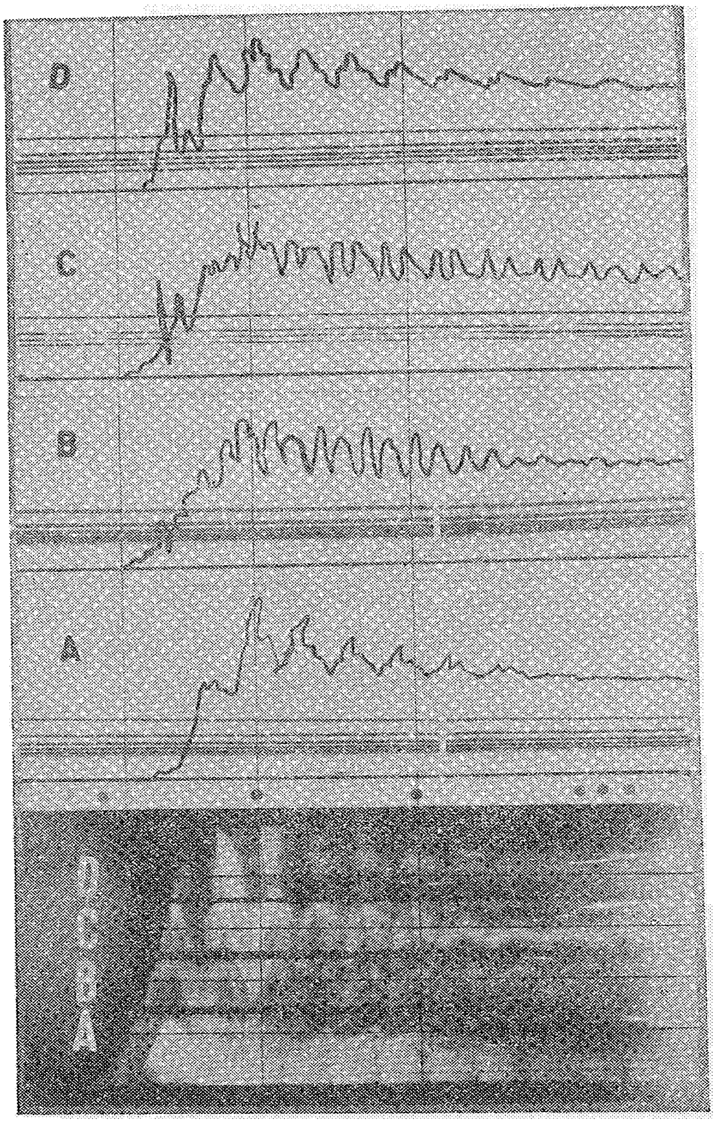


Plate I—Flame and Pressure Record

It should be noted that the timing dots shown on pressure card A correspond with the dots shown in the center of the flame photograph. The first dot at the left represents the spark that fired the charge. The narrow vertical lines across the plate were drawn to align the five photographs.

Inspection of the time-pressure curves B, C, and D, shows that there was a sharp rise and fall of pressure before the maximum pressure was attained. This sharp rise and fall of pressure under indicator C took place at a later time and was of a greater magnitude than that indicated by B, while the rise and fall of pressure indicated at D took place at a later time and was of a greater magnitude than that indicated by C.

The plot of the pressures throughout the length of the bomb as indicated at A, B, C, and D at the instant at which

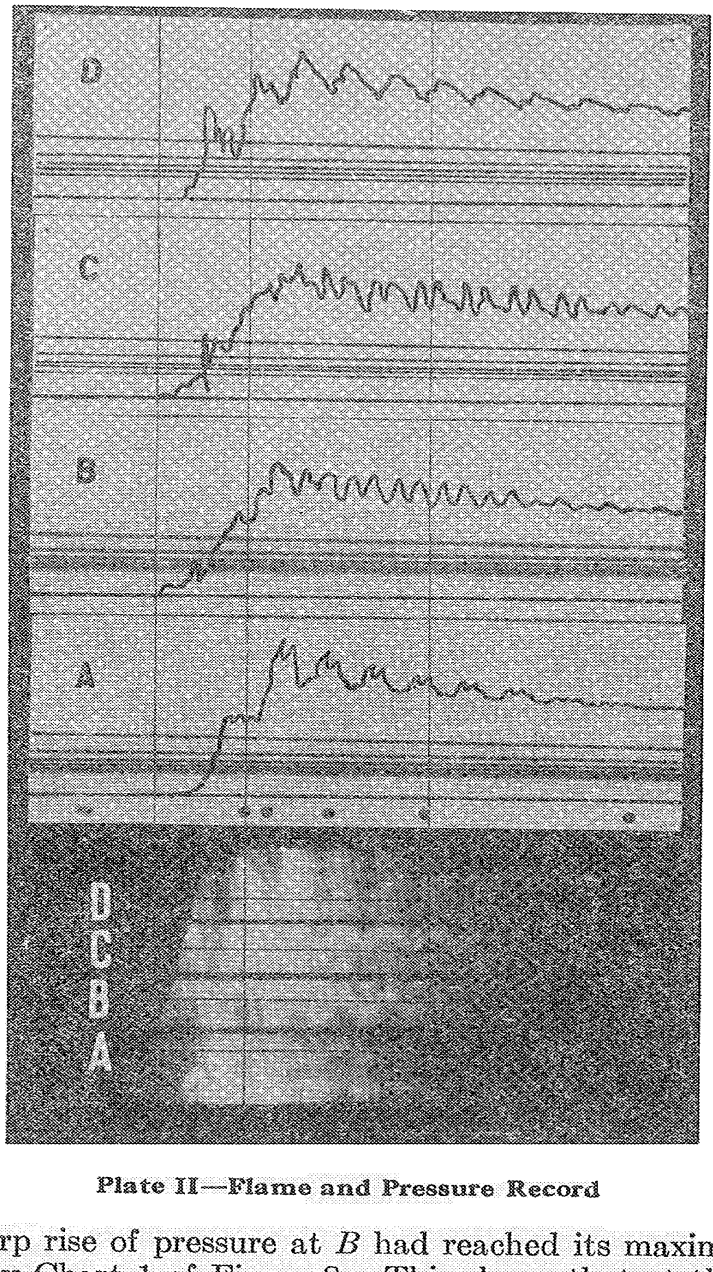


Plate II—Flame and Pressure Record

the sharp rise of pressure at B had reached its maximum is given by Chart 1 of Figure 8. This shows that at that instant when the greatest pressure along the bomb was in a position opposite indicator B, the flame front (F) had advanced past indicator C.

Figure 9 is a tracing of the flame photograph of Plate I rotated through 90 degrees so that the horizontal axis represents the length of the bomb and the vertical axis represents time with zero time at the top. Time 1 represents the instant at which the pressures were taken for Chart 1, Figure 8.

Chart 2, Figure 8, is similar to Chart 1 except that it represents the pressure distribution at time 2 (Figure 9) the instant at which the sharp rise and fall of pressure given

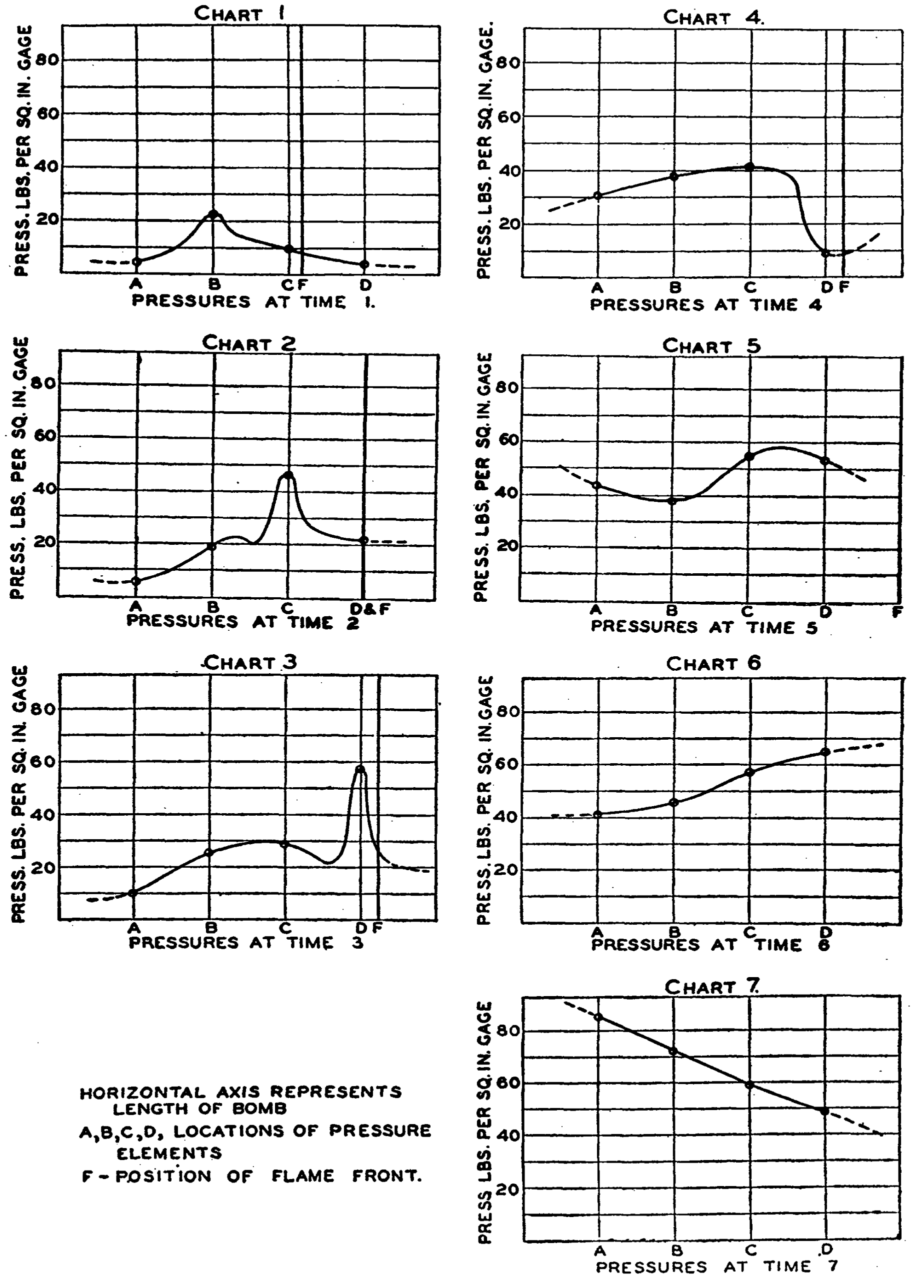


Figure 8—Pressure Distribution

by indicator *C* had reached its maximum. The flame front (*F*) had progressed to a position opposite indicator *D*.

Chart 3, Figure 8, represents the pressures along the bomb when the rapid rise and fall of pressures indicated at *D* had reached its maximum (time 3, Figure 9). The flame front had progressed to a position about half way between indicator *D* and the end of the bomb.

Chart 4 gives the pressures along the bomb when the flame had fallen back to its point of maximum recession given as time 4, Figure 9.

Chart 5 shows the pressures along the bomb when the flame front had reached the end of the bomb (time 5, Figure 9).

Charts 6 and 7 show the pressures along the bomb at later time intervals (times 6 and 7, Figure 9).

Charts 1, 2, and 3 show that a peak of pressure travels through the gas in back of the flame front and that this peak of pressure was traveling at a higher velocity than the flame front. The curve drawn through points 1, 2, and 3 of Figure 9 shows that the peak of pressure, or pressure wave, was increasing in velocity, and that it overtook the flame front at the same time that the flame halted. It is safe to assume that this pressure wave did not stop at the flame front but continued on ahead of the flame to the end of the bomb and was reflected therefrom.

As this pressure wave passes from the high-temperature medium behind the flame front into the relatively cool gases ahead of the flame, its velocity will probably decrease. In Plate I, and also Figure 9, the distance that this pressure wave travels through the relatively cool gases ahead of the flame front is so small that no definite conclusions may be reached from the experimental data as to whether this pressure wave continues with the same or with a decreased velocity. Comparison of the flame photograph with the time-pressure curves (Plate I) and the charts of Figure 8 clearly indicates that this pressure wave was reflected from the end of the bomb and entered the flame front at the point of recession of the flame. It then continued through the burning gases, being supported by the increase in the rate of combustion that it promoted. Upon reaching the firing end of the bomb it was again reflected and traveled back the length of the bomb, reaching the far end at approximately (slightly later than) the same time as the flame front. That a pressure wave travels the length of the bomb and back is substantiated by charts 6 and 7 (Figure 8) and also by the flame photograph.

This pressure wave traveling back and forth the length of the bomb caused variations in pressure throughout the bomb during the entire burning period, as shown by Plates I and II. These pressure curves (also charts 6 and 7, Figure 8) show that, when a peak of pressure occurs at one end of the bomb, a trough or low pressure occurs at the other.

These pressure curves and the flame photograph show that the peaks of pressure occurred when the flame was at maximum intensity, which point was just after the incandescent particles had changed direction.

Velocity of Reflected Wave—After the pressure in the bomb reached a maximum, the reflected pressure wave traveled at a constant velocity. This velocity is very easily measured by means of the contact prints of the original flame negatives. Scaling the photograph shows that the wave traveled the length of the bomb ten times in 2.032 cm. (0.8 inch) on the circumference of the flame drum. That is equivalent to 425 cm. per cm. (425 inches per inch) of film. The flame drum has a circumference of 159.5 cm. (62.8 inches) and travels at 63 r. p. m. Therefore, 1 cm. (1 inch) of film is equivalent to 0.00657 second (0.0167 second). This would give the wave a velocity of 646 meters (2120 feet) per second.

It is interesting to note what would be the approximate velocity of a sound wave traveling through this mixture under the same conditions. From the average pressure rise of 50 pounds gage, the approximate average temperature of the mixture can be computed as follows:

Average pressure rise, 3.515 kg. per sq. cm. (50 pounds per square inch)

Total average pressure, 4.554 kg. per sq. cm. (64.7 pounds per square inch)

Temperature corresponding to this pressure:

$(294° \text{ K.} \times 4.554) - 1.003 = 1294° \text{ K.}$

$(530° \text{ A.} \times 64.7) - 14.7 = 2330° \text{ A.}$

The velocity of sound in oxygen at 0° C. (32° F.) is given by Dulong as 317.2 meters (1041 feet) per second. The velocity of a wave in a gaseous media varies directly as the square root of the absolute temperature therefor:

$$V/\sqrt{T} = 317.2/\sqrt{294} = V/\sqrt{1294}$$
$$(V/\sqrt{T} = 1041/\sqrt{530} = V/\sqrt{2330})$$
$$V = 664.6 \text{ meters per second}$$
$$(V = 2180 \text{ feet per second})$$

The velocity of a sound wave in this mixture would, therefore, be approximately 664.6 meters (2180 feet) per second, which is very close to the actual velocity of the reflected wave shown in the photographs.

A sound wave set up by the igniting spark would travel ahead of the flame front, be reflected from the far end of the bomb, and meet the flame front when it had progressed to a position opposite pressure element *B* (Plate I). This sound wave, continuing on through the burning mixture at a higher velocity due to the increased temperature and pressure of the burning gases, would, after reflection from the firing end of the bomb, coincide with the observed pressure wave following the flame front. We have not yet established whether or not the coincidence of the reflected sound wave with the pressure wave is fortuitous.

At the ends of the bomb a trough or low pressure is found where the particles change their direction of motion from away from the end to toward the end of the bomb, and a crest or peak of pressure is found where the particles reverse their direction from toward the end to away from the end of the bomb.

Discussion

SOUND WAVE FROM IGNITING SPARK—When the sound wave set up by the igniting spark meets the flame front, part of the wave will continue on into the burning gases and part will be reflected from the flame front. The wave reflected from the flame front will tend to support the flame and carry the flame with it. The flame photograph (Plate I and Figure 9) shows that there is an increase in velocity of the flame front as it progresses from the position of contact with the sound wave (under indicator B) and that this velocity is the velocity of sound in the unburned gas.

The above interpretation does not agree with Dixon's idea that the sound wave set up by the igniting spark is the direct cause of the halt of the flame front, but rather, as will be indicated, may be the indirect cause of the halt of the flame front.

HALT OF FLAME FRONT—The sound wave set up by the

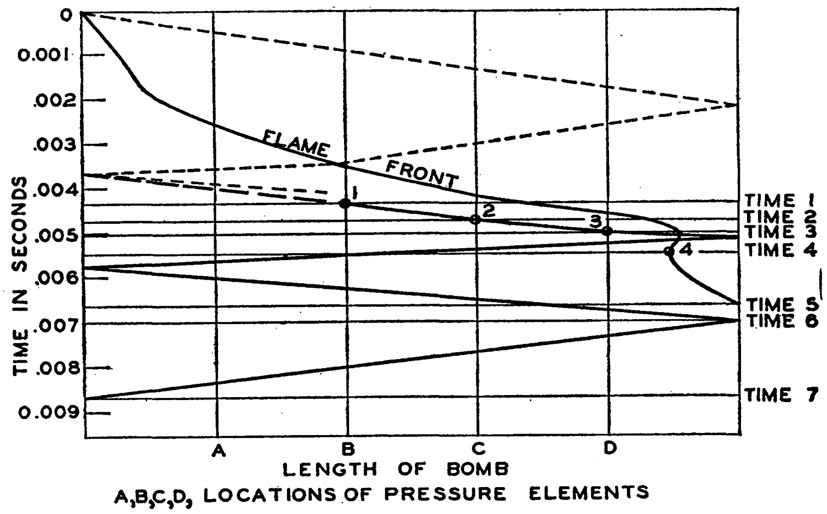


Figure 9—Sound Waves and Pressure Waves Accompanying the Flame Propagation

igniting spark, which passes into the burning mixture after meeting the flame front, will travel with an increased velocity due to the higher temperature and pressure in the burning gases. As has been indicated, this sound wave after reflection from the firing end of the bomb, almost coincides with the observed pressure wave following the flame front. As stated by Dixon, the sound wave, which is a pressure wave of low amplitude, might cause some increase in rate of combustion in the wave crest with consequent increase in the amplitude of the wave itself. If the coincidence of the sound wave and the pressure wave is not fortuitous, this might be an explanation of the source of the pressure wave following the flame front. However, no increase in rate of combustion was noted in any flame photograph as the sound wave reflected from the end of the bomb entered and passed through the burning gases.

This pressure wave as it increases in amplitude and as the medium through which it is passing increases in temperature and pressure, travels with increasing velocity. This wave, which is traveling with a greater velocity than the flame front, must overtake the flame front if the explosion chamber is of sufficient length. As has been previously shown, this pressure wave does overtake the flame front at the position at which the flame is halted.

The trough or low-pressure area following the peak pressure of the wave tends to decrease the rate of burning. The movement of the particles toward the rear of the flame and the decreased rate of burning cause the apparent halt and recession of the flame front.

Woodbury, Lewis, and Canby[3] have suggested that the pressure built up ahead of the flame is the cause of the halt of the flame front. The results here presented show that a pressure ahead of the flame front is the cause of the halt of the flame, but that the origin of this pressure is not that suggested by them.

Pressures Accompanying Flame—As has been previously shown (Figure 8), the pressures ahead of the flame front, although increasing as the flame progresses, are of much lower order of magnitude than those immediately following the flame front. Also, when the pressure ahead of the flame front becomes greater than the pressures behind the flame front, the flame is halted. This evidence is directly contrary to the theory presented by Midgley,[4] that the pressure ahead of the flame front must be greater than that behind the flame front if the flame is to be propagated into the unburned mixture.

Maximum Pressure Development as Related to the Flame—Previous investigators have disagreed as to the time of maximum pressure development as related to the inflammation of the mixture.

Woodbury, Lewis, and Canby[3] state that "the instant of maximum pressure development coincided with that of total inflammation of the gas." They present no conclusive evidence for their statement.

Dixon,[2] in discussing this point, says

> If the authors [Woodbury, Lewis, and Canby] mean by total inflammation the fact that the flame has spread from end to end of the vessel and that the whole column of gas is visibly alight, it may happen that the pressure is greatest at that moment, but in many cases, and I believe in most instances, the greatest mean pressure occurs after the flame has completely filled the vessel.

Hopkinson[5] proved by actual temperature and pressure measurements that the flame might fill the entire chamber some time previous to the attainment of maximum pressure.

Nagel[6] developed an elaborate mathematical analysis of rate of flame travel based on the assumption that the time of maximum pressure corresponds to the time of complete inflammation.

[5] *Proc. Roy. Soc.* (*London*), **77A**, 387 (1906).

[6] *Mitt. Forschungsarbeiten*, **54** (1908).

Wheeler,[7] working with a spherical bomb, reported that the time of total inflammation corresponded with that of maximum pressure development. He recorded the time interval between ignition of the charge and passage of the flame at a point 7.5 cm. from the point of ignition by means of the fusion of small copper wires placed at these points. This involved the assumption that the flame front produced sufficient heat to fuse the wire and that there was no time involved in the fusion. Also the fact that he recorded the passage of the flame at only one distance from the point of ignition would involve the assumption that the flame front traveled at a constant velocity.

Inspection of Plates I and II led us to agree with Dixon and Hopkinson that the time of maximum pressure may occur after the time of total inflammation, because at the time of total inflammation the mixture generally contains gases that are not completely burned by the initial flame.

DETONATION WAVE—As previously stated, our experimental results show that a pressure wave of high amplitude travels through the burning gases in back of the flame front, and that owing to its greater velocity it overtakes the flame front if the explosion chamber is of sufficient length. We also have shown that when the pressure wave overtakes the flame front the flame is halted.

In the case of more rapidly burning mixtures than here reported, a condition might result due to the higher temperatures developed, in which the pressure wave following the flame front would overtake the flame front at a time when its velocity would be only slightly less than that of the pressure wave. Under these conditions the flame front might be carried forward on the crest of the pressure wave instead of falling behind and being halted by it. This may be the mechanism by which the detonation wave is set up.

Conclusions

This paper is intended primarily to show the usefulness and possibilities of the apparatus here described. The experimental results so far obtained indicate that:

1—As the flame propagates through the explosive mixture, a pressure wave is set up in the burning mixture behind the flame front and travels at a greater velocity than the flame front.

2—The pressure in the crest of this wave behind the flame front is greater than the pressure in the flame front or in the unignited mixture ahead of the flame.

3—The halt and recession of the flame front is caused by the pressure wave, which follows the flame front at a greater velocity, overtaking and passing through the flame front.

4—The maximum pressure, in the case of mixtures promoting after-burning, is developed some time after total inflammation of the charge.

[7] *J. Chem. Soc. (London)*, **113**, 840 (1918).