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# THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

# SMALL-SCALE UNDERWATER EXPLOSIONS UNDER REDUCED ATMOSPHERIC PRESSURE

BY LT. D.C. CAMPBELL, USNR, AND C.W. WYCKOFF

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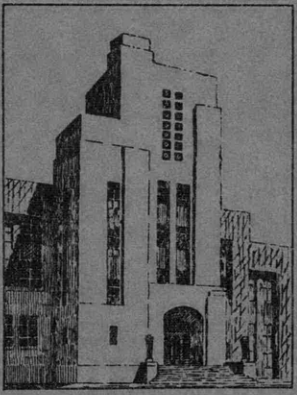

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NOVEMBER 1943

REPORT 520

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NAVY DEPARTMENT
DAVID TAYLOR MODEL BASIN
WASHINGTON, D.C.

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## REPORT 520

# SMALL-SCALE UNDERWATER EXPLOSIONS UNDER REDUCED ATMOSPHERIC PRESSURE

BY LT. D.C. CAMPBELL, USNR, AND C.W. WYCKOFF

NOVEMBER 1943

## PERSONNEL

The photographs in this report were taken at the David Taylor Model Basin by C.W. Wyckoff, with the aid of M.T. Sniffin, F.W. Bird, F.B. Kaye, and Lt. D.C. Campbell, USNR. The pressure-time records were made by H. Rich. The report was written by Mr. Wyckoff and Lieutenant Campbell.

# SMALL-SCALE UNDERWATER EXPLOSIONS UNDER REDUCED ATMOSPHERIC PRESSURE

## ABSTRACT

Tests have been conducted in the 24-inch variable pressure water tunnel to determine the effect of variation of pressure on the gas globe and shock wave produced in an underwater explosion. Recording was made by means of three types of high-speed photography: 1. Streak silhouette photographs, 2. Stroboscopic motion pictures, and 3. Micro-flash still pictures. The data obtained show good agreement with available theories. The pulse frequency decreases with increased globe diameter and the globe diameter increases with decreased pressure. There was no visible alteration in the form of the shock wave obtained at various pressures.

Some information is presented on the formation of cavitation bubbles. A suggestion of the relationship between the pulsating gas globe and the above-water plume is also presented.

## INTRODUCTION

In the small-scale explosion tests conducted at the David Taylor Model Basin for several years past (1) (2)* it has been recognized that the performance and behavior of the small charges used was not truly indicative of the behavior of large charges because the total pressure at the point of detonation, due to the atmosphere and the hydrostatic head of water, was not reduced to scale. This point was again raised by Professor G.I. Taylor during his visit to the United States in 1942, and during the ensuing discussion it became clearly evident that to obtain any reasonable scale relationship to larger charges, small-scale charges would have to be fired under reduced atmospheric pressures.

The 24-inch variable pressure water tunnel at the Taylor Model Basin offered the only ready means of conducting explosion tests under these conditions. The work proceeded accordingly, although it was known from the beginning that the charges would all have to be very small.

The object of these tests was fourfold:

1. To measure the maximum diameters of gas globes produced by very small underwater explosions under various total pressures and depths of water.

2. To determine variations in the time of the first pulsation of the gas globes with changes in total pressure and water depth.

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* Numbers in parentheses indicate references on page 31 of this report.

3. To compare charges of various sizes.
4. To observe any unusual incidental phenomena.

## TEST APPARATUS AND PROCEDURE

The nozzles were removed from the water tunnel test section* to give the greatest free volume of water. The access hatch in the top of the tunnel was fitted with an airtight packing gland which contained the charge support and the firing leads.

Two types of charges were used in these experiments. The principal one investigated was the Hercules ND-24 cannon primer or half-cap. It contained** 0.09 gram of a mixture composed of 75 per cent diazodinitrophenol and 25 per cent potassium chlorate. The other charge was a Number 6 du Pont electric blasting cap.

The results were recorded photographically by three different methods which are described in the following.

The setup of apparatus for the streak silhouette photographs is shown in Figure 1. The film in the General Radio camera is allowed to move past an open shutter and a narrow slit 3/32 inch wide replacing the film gate. Any light caught by the camera lens is then recorded as a streak on the film. In these tests the photoflood lamps on the north side of the test section left a streak on the film, which was interrupted by the silhouette of the gas globe. There is obtained in this manner a record of globe diameter, in one plane, as a function of time. The timing and film velocity are obtained from a 60-cycle stroboscope impulse which, transformed through a spark coil, leaves a small mark on the edge of the film. To establish a scale for determining the size of the globe in the field, two short pieces of wire were attached to the firing lead a known distance apart as shown in Figure 2. A sample record showing the scale streaks and the globe silhouette is reproduced in Figure 3.

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* Details of the test section are shown on Sheets K-20, 21, and 23 of the TMB Equipment Information Booklet.

** See the Appendix, page 32.

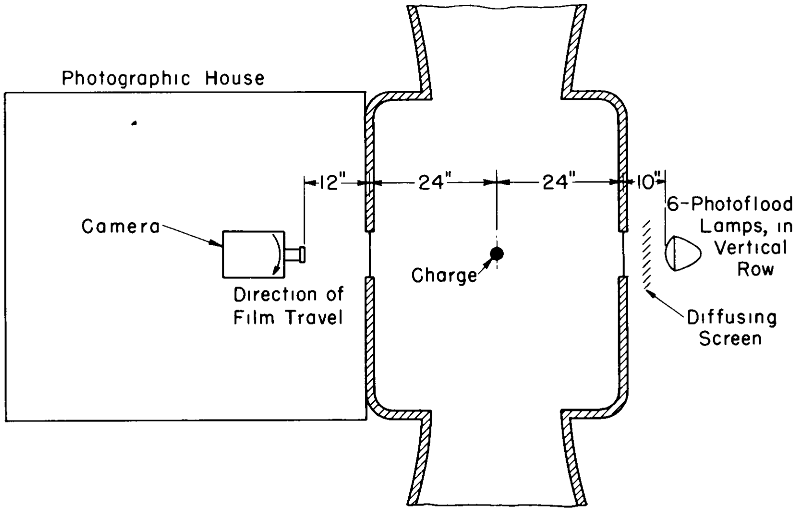
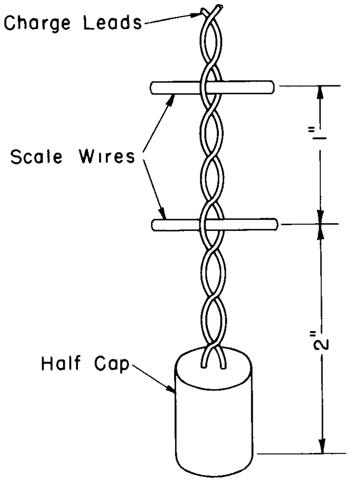


Figure 1 - Plan View of 24-Inch Water Tunnel, arranged for obtaining Streak Silhouette Records of Small Underwater Explosions

A glass port placed in the door on the north (right) side of the test section admitted light from six 2R photoflood lamps arranged in a vertical row. The camera, of the General Radio oscillograph type, placed opposite the south glass port, was equipped with a special narrow film gate, perpendicular to the direction of film travel.

Figure 2 - Charge as arranged for Streak Silhouette Records

The two wires placed one inch apart in the firing leads serve as a scale.



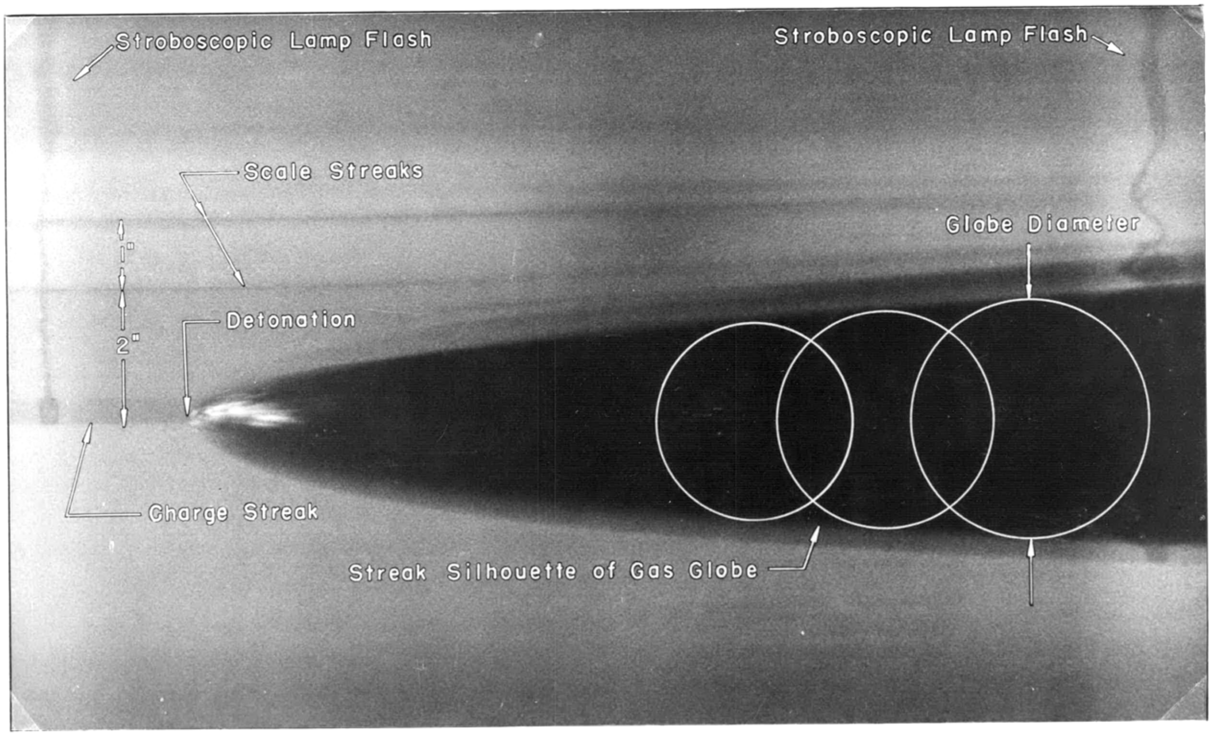


Figure 3a - This record shows an enlarged section at the start of the explosion. The film is traveling at 570 inches per second, giving a time-diameter record (in one plane) of the globe motion. A stroboscopic light flashing every 0.0013 second leaves, in addition to the streaks, a narrow still picture of the action at that time.

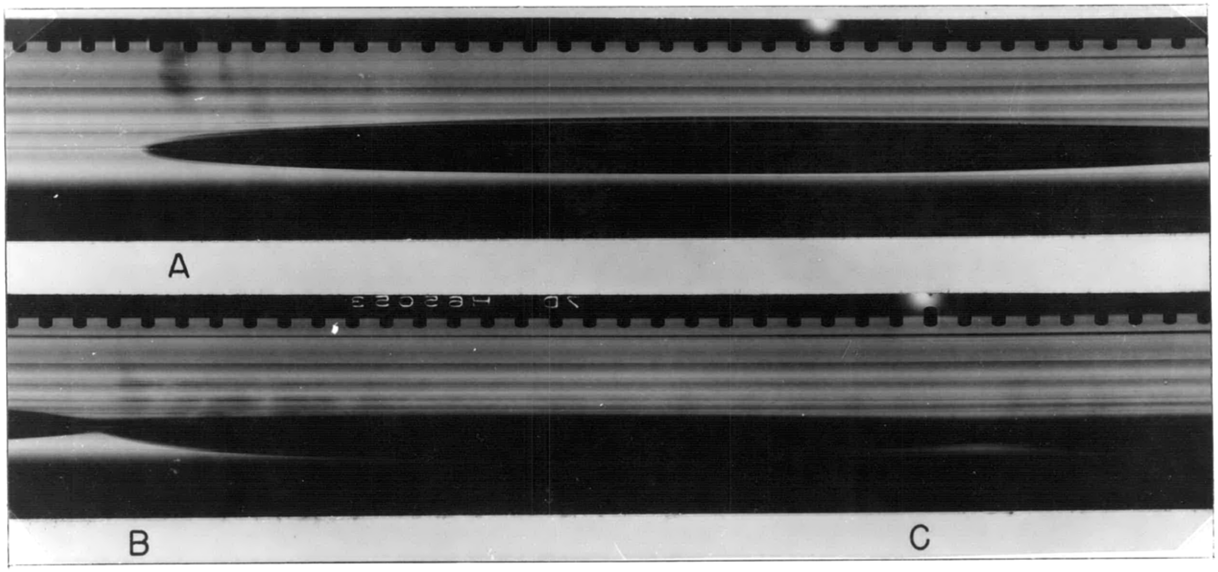
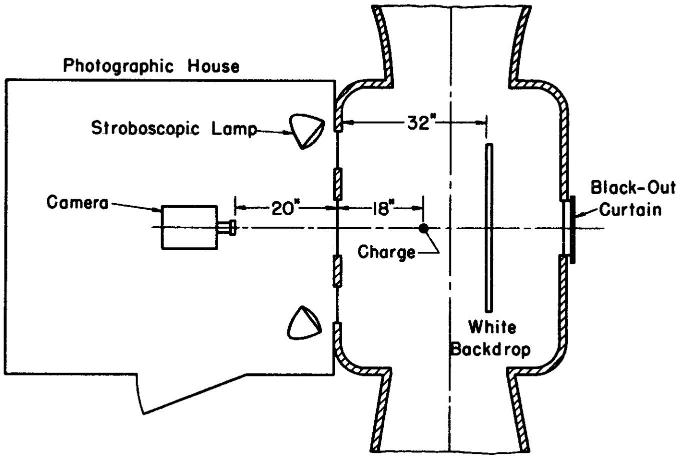
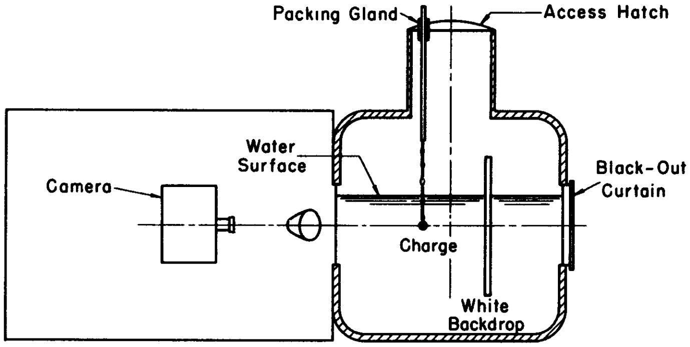


Figure 3b - This photograph was made at a depth of 9 inches and an absolute pressure of 9.0 pounds per square inch. Bubble formations in the liquid outside the gas globes are indicated by smears in positions A, B, and C. This record reveals bubble oscillations not shown on the motion pictures. A large bubble formation which pulsates for at least 3 cycles may be seen at A. Immediately following the first and second gas globe contraction, smaller bubble formations may be seen at B and C. These bubbles appear to pulsate for greater periods of time than those at A.

Figure 3 - Streak Silhouette Records of Underwater Explosions



SECTIONAL PLAN VIEW



ELEVATION

Figure 4 - Equipment Setup for High-Speed Motion Pictures

This diagram illustrates the setup used in obtaining high-speed motion pictures of small underwater explosions in the 24-inch variable pressure water tunnel. A 2-foot square white backdrop placed 14 inches behind the charge serves as a reflector for the stroboscopic lights. The lights in the photographic house were directed through glass ports placed on either side of the camera port. The camera, in an upright position, is of the General Radio stroboscopic motion picture type. The charge depth was regulated by varying the water level.

## HIGH-SPEED MOTION PICTURES

High-speed motion pictures (3), capable of projection, were obtained by use of the General Radio stroboscopic equipment (4) as shown in Figure 4. The majority of pictures were taken at a film rate of 1100 frames per second. The film-scale factor was obtained from alternate pieces of black and white tape fixed to the firing leads.

## MICRO-FLASH STILL PHOTOGRAPHS

Figure 5 shows the arrangement used in taking the micro-flash still photographs (5) (6). The charge was suspended as before, with alternate black and white tape on the leads serving as a scale. The pictures were obtained

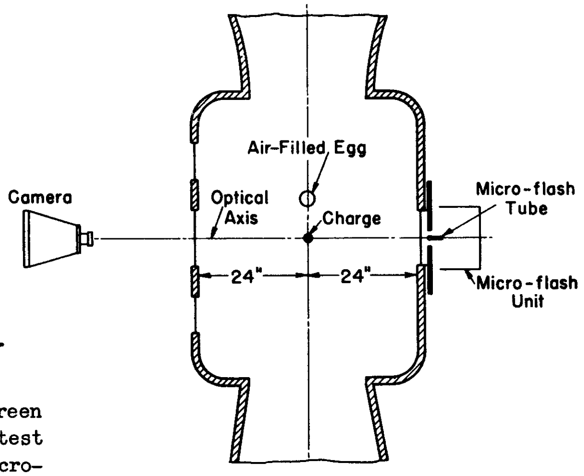
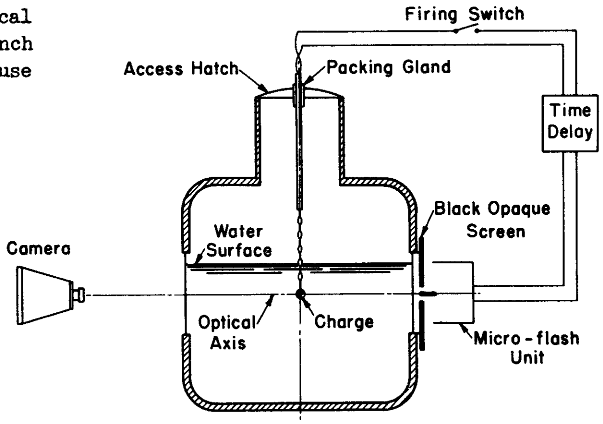


Figure 5 - Arrangement for Micro-Flash Still Photographs

A hole 1 inch in diameter was cut in an opaque screen covering the port on the north side of the test section of the 24-inch water tunnel. The micro-flash tube was placed behind this hole on the optical axis of the camera. The camera, a 4-inch by 5-inch Speed Graphic, was located in the photographic house on the opposite side of the tunnel.



by the method illustrated schematically in Figure 6. A time-delay mechanism, TMB time-delay circuit 1 (7), trips the micro-flash lamp a short interval of time after the detonation ruptures the charge filament. The shock wave compresses the water to a higher density and some form of light reflection or refraction occurs at the interface between the media of different densities. The gas globe serves to shield the camera from the direct rays of light, as the shutter is open throughout this entire process. The optics of this method are not completely understood, and a course of investigation has been undertaken to determine the actual light paths.

Some pressure-time measurements were taken in conjunction with the micro-flash still photographs. The measurements were made by a tourmaline crystal pressure gage and a cathode-ray oscillograph (8). The movement of the beam across the oscillograph tube was initiated by the TMB firing-trigger circuit 1 at the moment of breaking of the charge bridge wire.

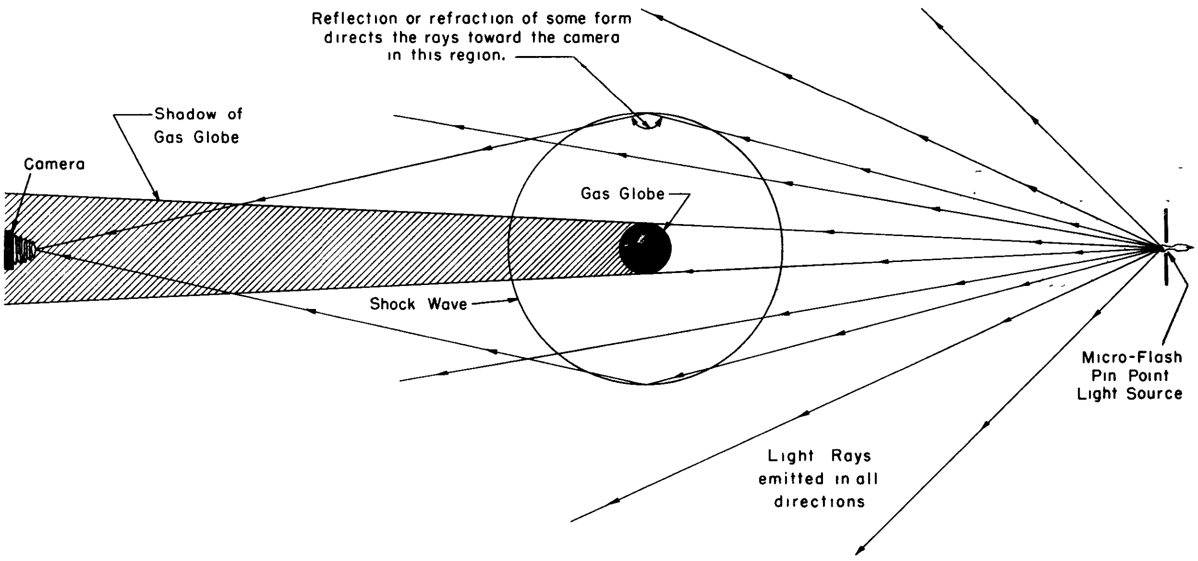


Figure 6 - Schematic Diagram of Method of Recording Shock Wave

## TEST RESULTS

### STREAK PHOTOGRAPHS

Figure 3b on page 4 is given as a sample streak silhouette, in which the first two and one-half gas globe pulsations are clearly shown. One other silhouette is reproduced in Figure 13 on page 16. Photographic records of this kind were obtained under the following test conditions:

1. At an 18-inch depth of water half-caps were fired at total pressures of 15 [4],* 13 [3], 11, 9 [2], 7, 5 [2], 3.7, 3, 1.6, and 1.2 [3] pounds per square inch absolute.

2. With half-caps at a 9-inch depth of water and at total pressures of 15, 13, 11, 9, 7, 5, 3, and 1 pounds per square inch absolute.

3. At a depth of approximately 10 inches of water du Pont Number 6 caps were fired at total pressures of 15, 11, 9, and 7 pounds per square inch absolute.

The data obtained from these records are set down in Tables 1 and 2 on page 8 and are plotted in Figures 9, 10, and 11, on pages 12 and 13.

### HIGH-SPEED MOTION PICTURES

A section of a motion picture film taken at 1100 frames per second is reproduced in Figure 7. It shows the explosion of a half-cap in 18 inches of water under a pressure of 15 pounds per square inch absolute. Other similar pictures are reproduced in Figures 12, 15, 16, 18, 19, and 20.

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* The numbers in the brackets indicate the number of charges fired under identical conditions.

## TABLE 1

## Data Obtained from Streak Silhouettes of Half-Cap Explosions in the 24-Inch Water Tunnel

These data are plotted in Figures 10, 11, and 21.

| Total Absolute Pressure at the Charge | | Depth of Charge below Water Surface $d$ inches | Maximum Globe Diameter First Pulse $D_1$ inches | Energy of Pulse Motion First Pulse $E_1$ inch-pounds | Time of First Pulse $T_1$ seconds | Maximum Globe Diameter Second Pulse $D_2$ inches | Energy of Pulse Motion Second Pulse $E_2$ inch-pounds | Time of Second Pulse $T_2$ seconds | Maximum Globe Diameter Third Pulse $D_3$ inches | Energy of Pulse Motion Third Pulse $E_3$ inch-pounds | Time of Third Pulse $T_3$ seconds |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $P$ lb/in$^2$ | Equivalent Depth of Fresh Water inches* | | | | | | | | | | |
| 15 | 415 | 18 | 6.4 | 2070 | | | | | | | |
| 15 | 415 | 18 | 6.2 | 1870 | | | | | | | |
| 15 | 415 | 18 | 5.8 | 1540 | 0.0139 | 4.0 | 503 | 0.0094 | | | |
| 15 | 415 | 18 | 5.5 | 1310 | 0.0132 | 3.3 | 282 | 0.0087 | 2.7 | 155 | 0.0075 |
| 13 | 360 | 18 | 5.4 | 1070 | 0.0155 | 3.0 | 184 | 0.0100 | 2.5 | 106 | 0.0089 |
| 13 | 360 | 18 | 6.4 | 1790 | 0.0157 | 5.4 | 1070 | 0.0105 | 4.9 | 801 | 0.0093 |
| 13 | 360 | 18 | 6.2 | 1630 | 0.0154 | 4.5 | 621 | 0.0114 | 4.2 | 505 | 0.0089 |
| 11 | 304 | 18 | 7.0 | 1980 | 0.0178 | 4.6 | 561 | 0.0128 | 4.1 | 397 | 0.0109 |
| 9 | 249 | 18 | 7.1 | 1690 | 0.0218 | 4.5 | 430 | 0.0148 | 4.0 | 302 | 0.0129 |
| 9 | 249 | 18 | 6.2 | 1120 | 0.0201 | 3.6 | 220 | 0.0135 | 2.9 | 115 | 0.0114 |
| 7 | 194 | 18 | 7.6 | 1610 | | 4.5 | 334 | | 3.1 | 109 | |
| 5 | 138 | 18 | 8.7 | 1730 | 0.0342 | 5.1 | 348 | 0.0216 | 4.5 | 239 | 0.0194 |
| 5 | 138 | 18 | 7.6 | 1150 | 0.0340 | 4.0 | 168 | 0.0218 | 3.2 | 86 | 0.0210 |
| 3.7 | 102 | 18 | 9.1 | 1460 | 0.0464 | 6.4 | 508 | 0.0322 | | | |
| 3 | 83 | 18 | 9.1 | 1180 | 0.0540 | | | | | | |
| 1.6 | 44 | 18 | 11.8 | 1380 | 0.0970 | | | | | | |
| 1.2 | 33 | 18 | 15.6 | 2370 | | | | | | | |
| 1.2 | 33 | 18 | 16.9 | 3030 | | | | | | | |
| 1.2 | 33 | 18 | 15 + | | 0.0133 | | | | | | |
| 15 | 415 | 9 | 5.8 | 1540 | 0.0132 | 4.5 | 716 | 0.0096 | 3.5 | 337 | 0.0087 |
| 13 | 360 | 9 | 6.0 | 1470 | 0.0148 | 4.7 | 707 | 0.0110 | 3.3 | 245 | 0.0091 |
| 11 | 304 | 9 | 6.4 | 1520 | 0.0171 | 4.5 | 525 | 0.0128 | 3.6 | 269 | 0.0117 |
| 9 | 249 | 9 | 7.3 | 1840 | 0.0204 | 5.5 | 785 | 0.0153 | | | |
| 7 | 194 | 9 | 7.6 | 1610 | 0.0246 | | | 0.0187 | | | 0.0055 |
| 5 | 138 | 9 | 8.7 | 1730 | 0.0333 | | | 0.0239 | | | |
| 3 | 83 | 9 | 10.4 | 1770 | 0.0500 | 6.0 | 340 | 0.0320 | | | |
| 1 | 28 | 9 | 17 + | | 0.0124 | | | | | | |

* One cubic foot of water = 62.425 pounds

## TABLE 2

## Data Obtained from Streak Silhouettes of du Pont Number 6 Caps Fired in the 24-Inch Water Tunnel

These data are plotted in Figure 9.

| Total Absolute Pressure at the Charge | | Depth of Charge below Water Surface $d$ inches | Maximum Globe Diameter First Pulse $D_1$ inches | Time of First Pulse $T_1$ seconds | Energy of Pulse Motion First Pulse $E_1$ inch-pounds |
|---|---|---|---|---|---|
| $P$ pounds per square inch | Equivalent Depth of Fresh Water inches | | | | |
| 15 | 415 | 10 ± 0.2 | 9.4 | 0.021 | 6330 |
| 11 | 304 | 10 ± 0.2 | 10.0 | 0.025 | 5760 |
| 9 | 249 | 10 ± 0.2 | 10.4 | 0.030 | 5300 |
| 7 | 194 | 10 ± 0.2 | 11.2 | 0.039 | 5140 |

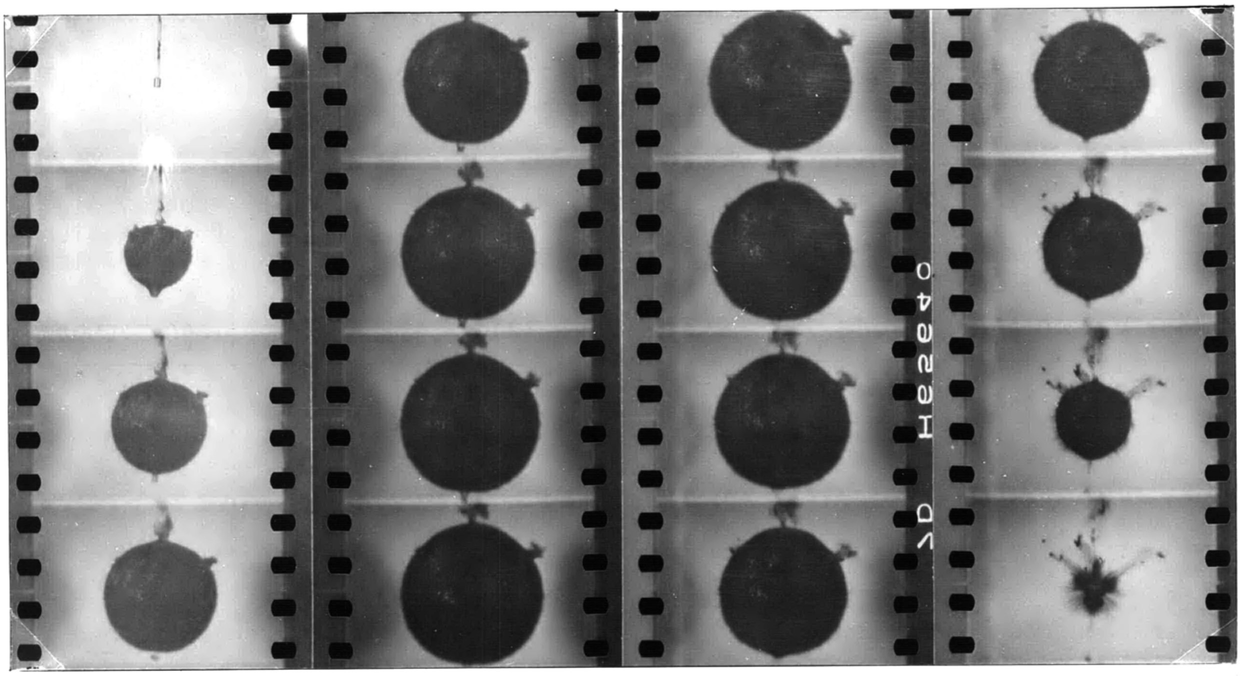

Figure 7 - Section of High-Speed Motion Picture

This is a typical high-speed motion picture taken in the 24-inch variable pressure water tunnel at a rate of 1100 frames per second. The subject is the explosion of a Hercules ND-24 cannon primer (half-cap) at a depth of 18 inches with a total pressure of 15 pounds per square inch.

High-speed motion pictures were obtained under the following test conditions:

1. Half-caps fired at an 18-inch depth of water and at pressures of 15 [5], 4 [1], 1.39, 1.22, 1.03, and 1.00 pounds per square inch absolute.

2. Number 6 du Pont caps fired at a 10-inch depth of water and at pressures of 15 [2], 13.9, and 7 [2] pounds per square inch absolute.

3. Half-caps with the camera placed to show both the above-water and the underwater action were fired under the following conditions:

| Charge Depth inches | Total Absolute Pressure at Charge pounds per square inch | | | | |
|---|---|---|---|---|---|
| 1 | 15 | 5 | 3 | | |
| 1 1/2 | 15 | 10 | 5 | 1 | |
| 6 | 15 [3] | 4 [3] | 1.64 | 1.59 | 1.10 |

4. Half-caps were placed in the tunnel and left overnight under a reduced pressure of approximately 2 pounds per square inch absolute. They were then fired the following morning. It was intended that by subjecting the

TABLE 3

Controlled-Air Half-Cap Shots

These data are plotted in Figures 10, 11, and 21.

| Absolute Pressure at the Charge | | Time Under Reduced Pressure hr min | | Depth inches | Maximum Globe Diameter $D_1$ inches | Time of First Pulse $T_1$ seconds | Energy of Pulse Motion First Pulse $E_1$ inch-pounds |
|---|---|---|---|---|---|---|---|
| $P$ pounds per square inch | Equivalent Depth of Fresh Water inches | hr | min | | | | |
| 15 | 415 | 19 | 7 | 4.5 | 5.8 | 0.013 | 1530 |
| 10 | 277 | 19 | 20 | 4.3 | 6.7 | 0.018 | 1570 |
| 5 | 138 | 19 | 15 | 4.7 | 8.8 | 0.032 | 1720 |
| 1 | 28 | 20 | 0 | 4.0 | 15.5 | 0.080 | 1770 |

water to a reduced pressure for a considerable time, most of the entrained air would be removed. It is possible that this condition was partially achieved, at least for the water in the test chamber of the tunnel. The data from these shots are given in Table 3.

5. Air-filled egg shells were suspended at a 4-inch depth of water, and at 3 [3], 6, 9, and 12 inches horizontally from the half-cap. All explosions were made with atmospheric pressure on top of the water surface.

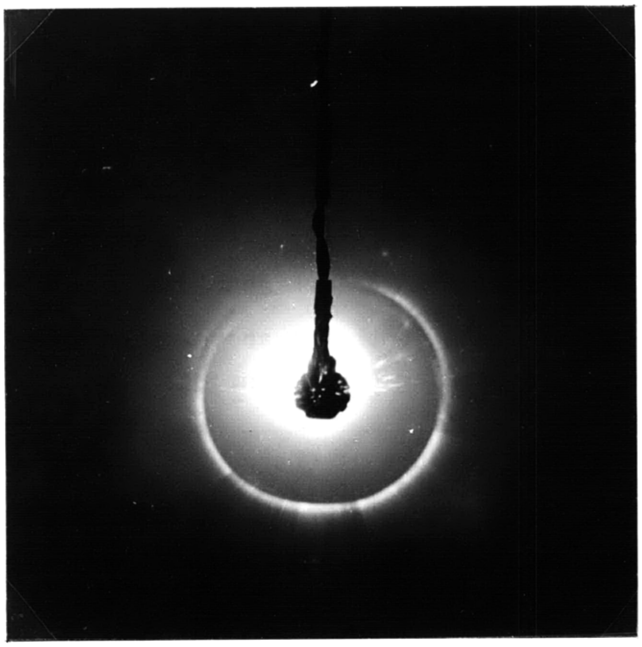

Figure 8 - Sample Micro-Flash Photograph

This photograph taken at atmospheric pressure and 19 microseconds after detonation, shows the shock wave at 2 1/4 inches diameter.

MICRO-FLASH STILL PICTURES

A representative micro-flash still picture is shown in Figure 8. This picture shows the gas globe and shock wave approximately 19 microseconds after detonation. Others are reproduced later in this report in Figures 23, 24, 25, 26, and 27 on pages 25 to 30.

Micro-flash still photographs were obtained under the following test conditions:

1. Half-cap explosions

| Pressure pounds per square inch | Depth inches | Time Delay microseconds |
|---|---|---|
| 7.0 | 6 | 20 + K* = 39 |
| 14.7 | 6 | 20 + K = 39 |
| 14.8 | 4 | 0 + K [4]** = 19 |
| 14.8 | 4 | 20 + K [3] = 39 |
| 14.8 | 4 | 50 + K [1] = 69 |
| 14.8 | 4 | 70 + K [1] = 89 |

* K is the time delay in the TMB micro-flash unit. This inherent delay of the micro-flash unit is due to the spark coil circuit and had not been previously determined. Figure 25a is an example of this delay. With a zero time-delay setting the shock wave is photographed with a diameter of 2.25 inches. Assuming the velocity of the shock wave to be the same as that of sound, or 5000 feet per second, the delay in the lamp is 19 microseconds.

** The numbers in brackets indicate the number of charges fired under identical conditions.

2. Air-filled egg shells at a 4-inch depth of water and placed 3 inches horizontally from half-caps fired with 59, 119, and 5019 microseconds time delay. All the delay times given include the K-factor. These photographs may be seen in Figure 26 on pages 28 and 29.

3. Piezoelectric pressure gage at 4-inch depth of water under the conditions given in Table 4.

TABLE 4

Comparison of Half-Cap Shock Wave Records obtained by Photographs and Pressure Records

| Piezoelectric Pressure Gage | | | Micro-Flash Still Photographs | | | |
|---|---|---|---|---|---|---|
| Time of Transit Charge to Gage microseconds | Horizontal Charge-Gage Distance inches* | Peak Pressure pounds per square inch | Charge-Gage Distance inches | Charge-Shock Wave Distance inches | Time Delay microseconds | Distance Wave should travel inches* |
| 62 | 3.7 | 691 | 3.4 | 3.2 | 59 | 3.5 |
| 68 | 4.1 | 576 | 4.6 | 4.9 | 82 | 4.9 |
| 77 | 4.7 | 533 | 5.0 | 5.2 | 89 | 5.3 |

* This value was obtained by assuming the velocity of the shock wave to be 5000 feet per second.

## DISCUSSION OF RESULTS

Examination of the results of firing the caps under varying pressures reveals that the maximum globe diameter increases with a decrease in the absolute pressure. The time required for one cycle also increases with decreasing pressure. As will be noted on the curves of Figures 9, 10, and 11, there is not complete agreement between the various points. A check on the order and time of reading was made in an endeavor to discover any reason for the discrepancy. The air content of the water is the only apparent variable which was not taken into account.

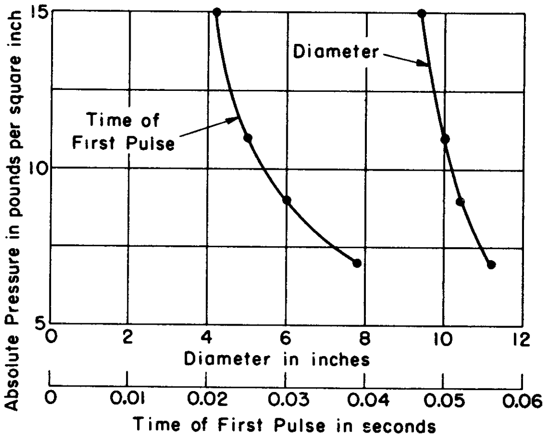

Figure 9 - Relation between Globe Diameter and Time of First Pulse and the Absolute Pressure in the Water

The data are for du Pont Number 6 caps fired at a water depth of 10 ± 0.2 inches.

Cavitation bubbles* appeared in the water surrounding the gas globe. In some cases, these bubbles were more pronounced than in others. The prints taken from the motion picture, Figure 12, show:

(a) small bubbles appearing less than 1 millisecond after detonation. These bubbles immediately disappear.

(b) the small bubbles reappear 4 1/2 milliseconds later. They remain for approximately 3 milliseconds, during which time they appear to grow gradually to a maximum diameter of 1/4 inch and again disappear.

(c) a few scattered bubbles appear 6 1/2 milliseconds later.

(d) 5 1/2 milliseconds after the point of first contraction of the gas globe, small clusters of bubbles appear and remain visible for 2 milliseconds. No more bubbles are noticed on this record.

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* Throughout this report, the term "bubbles" refers to minor spheroids filled with air or water vapor, such as those due to cavitation; "globe" refers to the large spheroid containing the products of combustion.

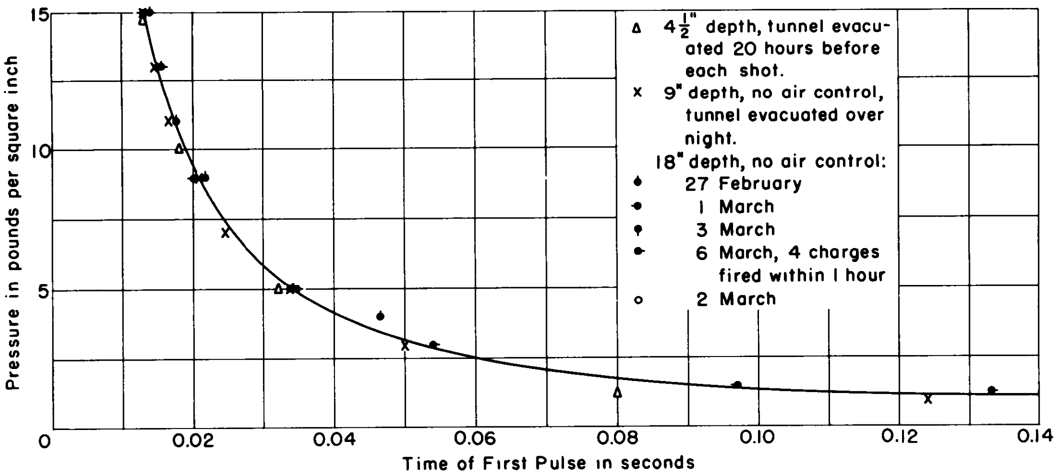


Figure 10 - Relation between Time of First Pulse and Absolute Pressure in the Water

The data are for half-caps fired in the 24-inch water tunnel.

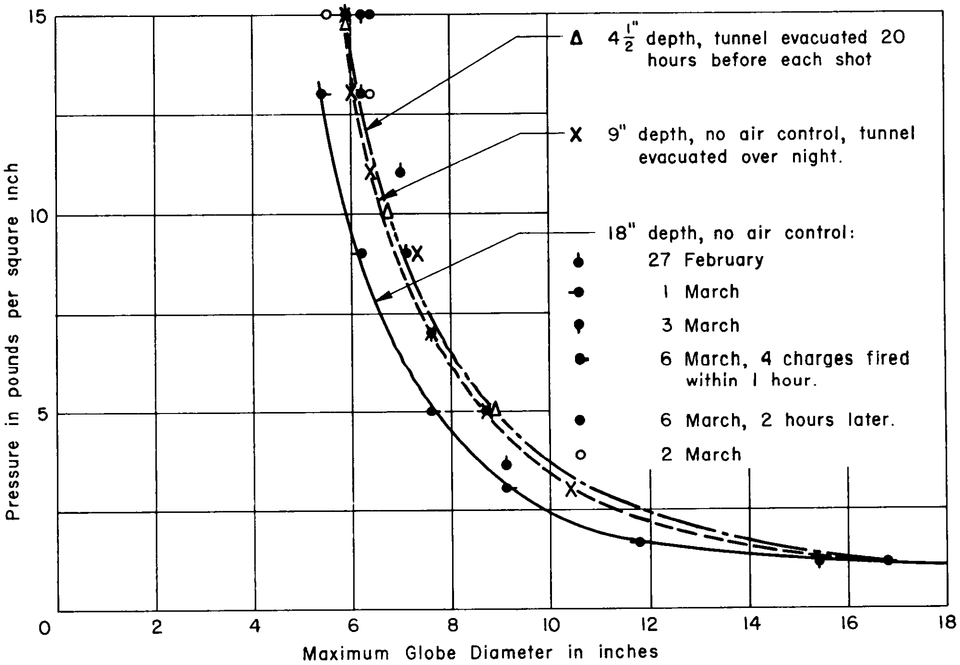
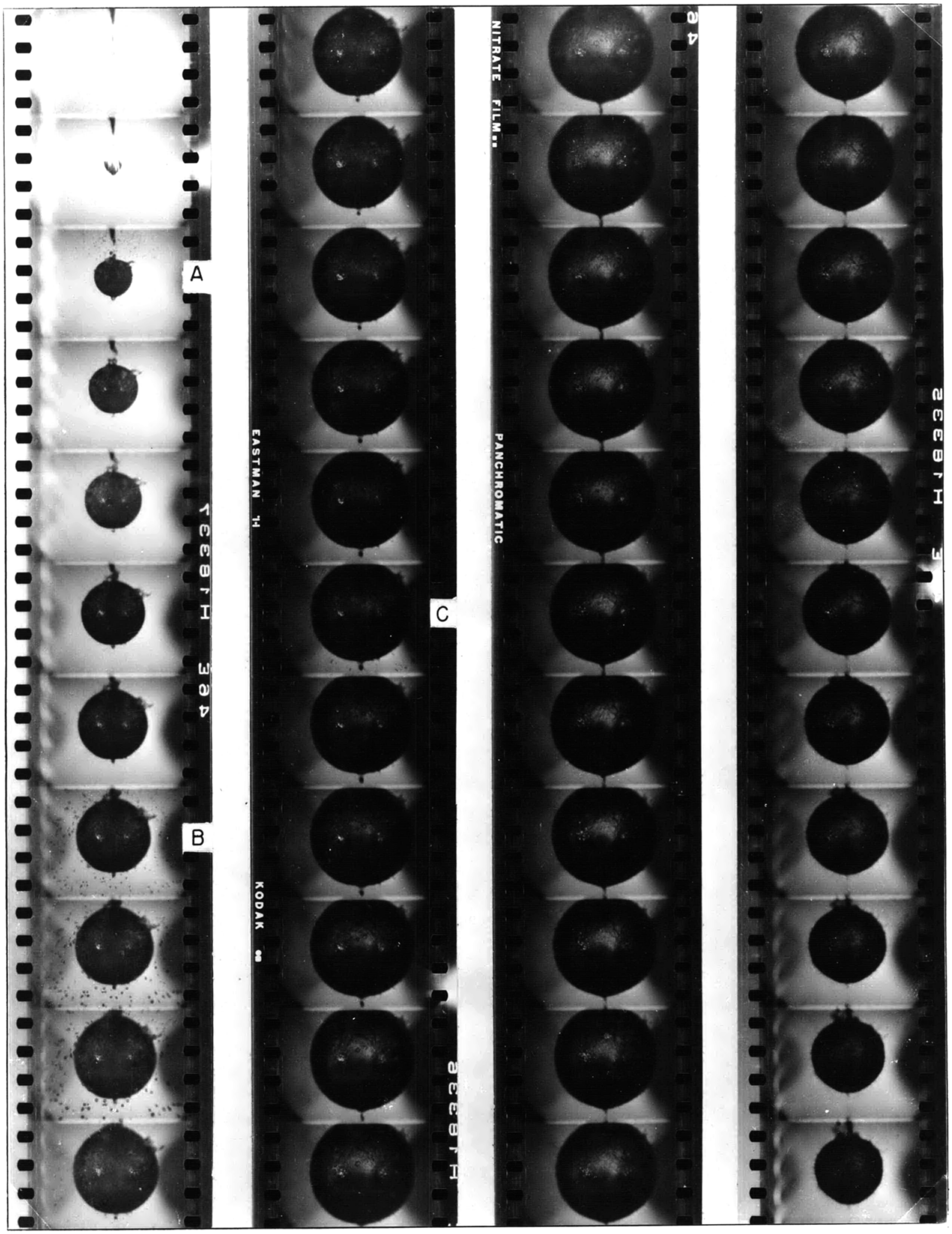


Figure 11 - Relation between Maximum Gas Globe Diameter and Absolute Pressure in the Water

These data were obtained from half-cap explosions.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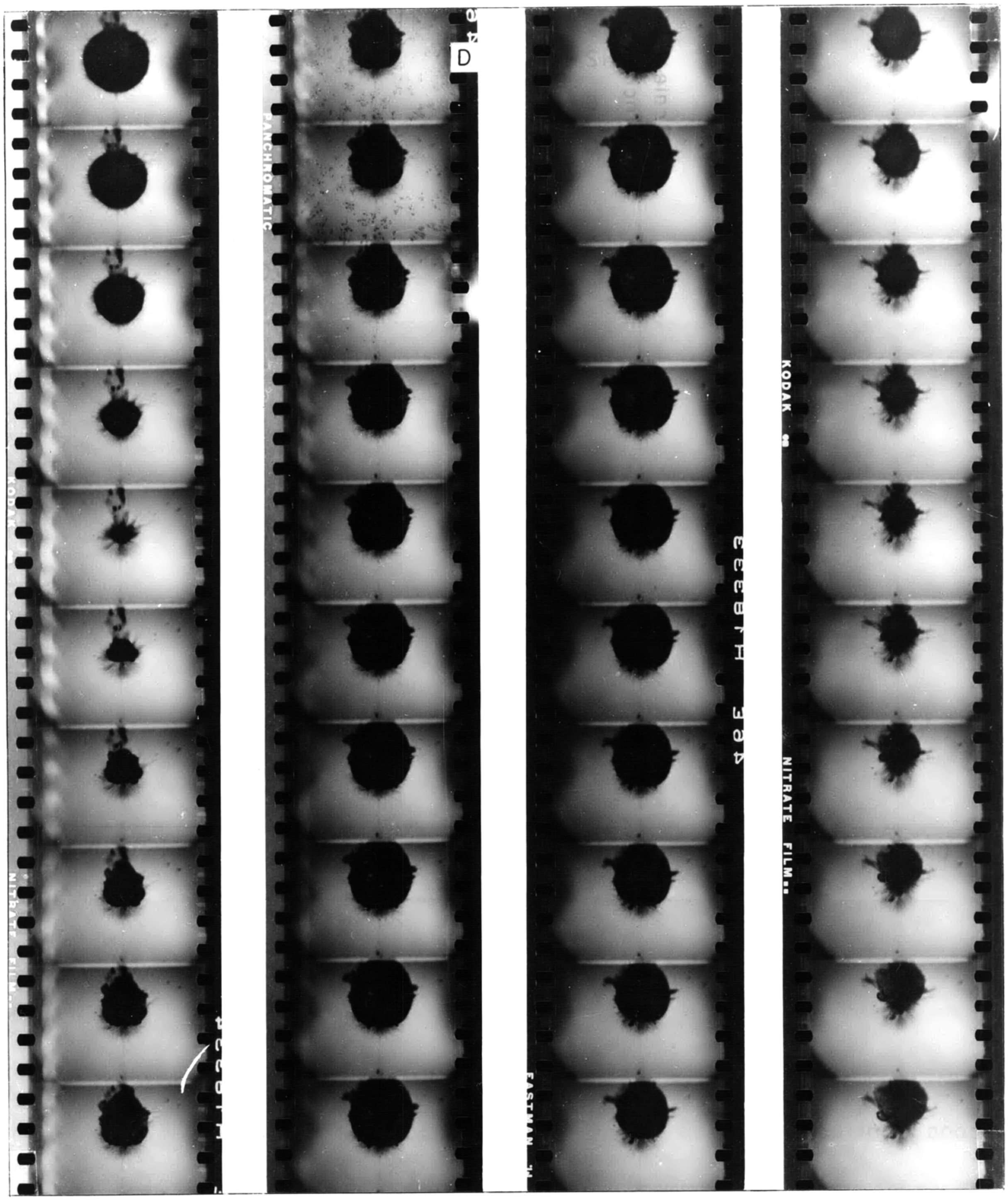

Figure 12 - High-Speed Motion Picture of the Explosion of a Half-Cap in Water

The cap was 18 inches below the water surface in the 24-inch water tunnel at a pressure of 4.0 pounds per square inch absolute. Positions A, B, C, and D show bubble formation outside the gas globe as referred to in the text on page 12. The film speed is roughly 1100 frames per second.

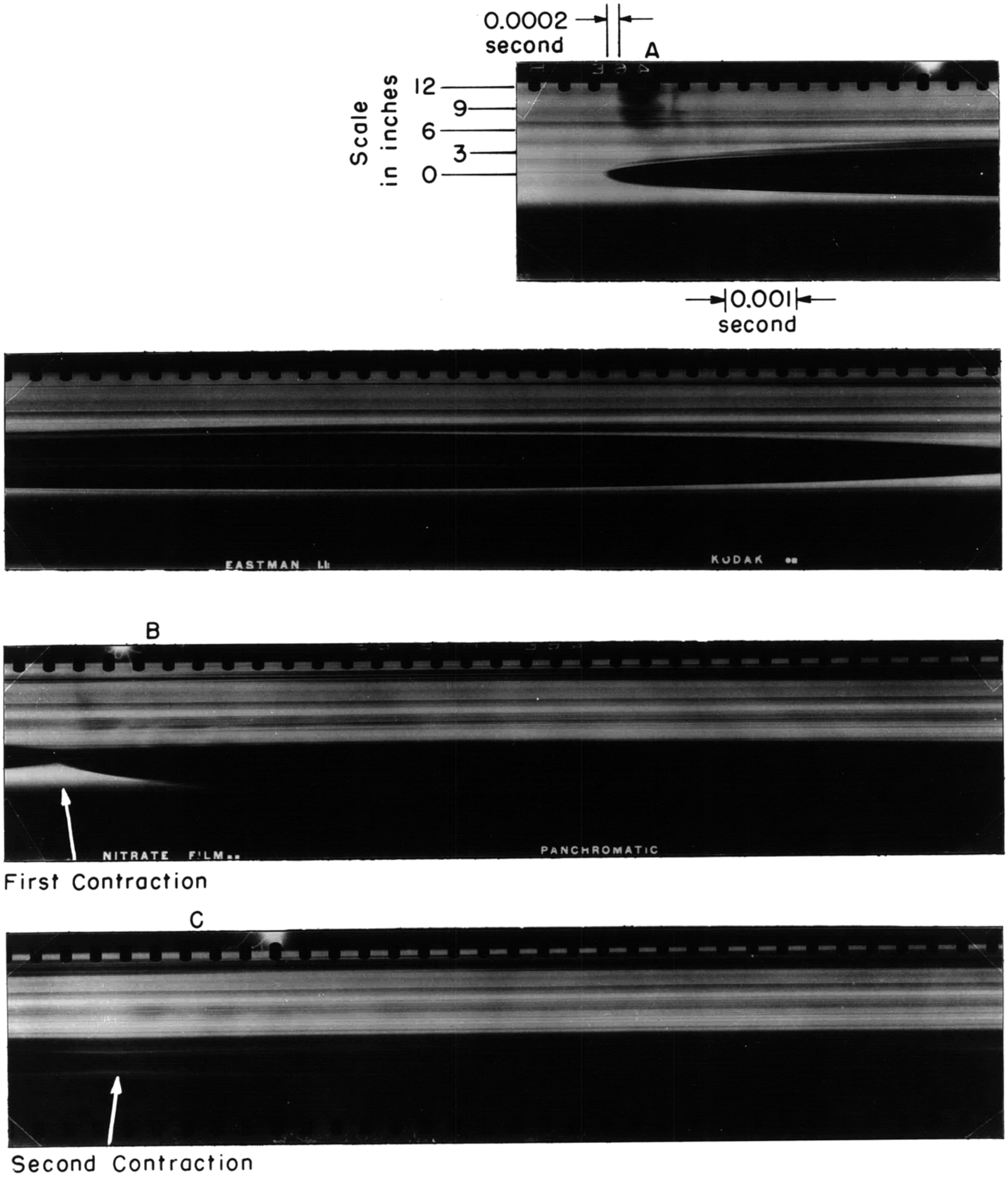

Figure 13 - Streak Silhouette Photograph of the Explosion of a Half-Cap in Water

This photograph was made at a depth of 9 inches of water and an absolute pressure of 9.0 pounds per square inch. Bubble formations in the liquid outside the gas globe are indicated at the positions A, B, and C. At A the bubbles pulsate for at least three cycles. Immediately following the first and second gas globe contraction, smaller bubble formations may be seen at B and C, which pulsate for greater periods of time. This silhouette shows migration downward of the globe as well as its pulsation.

The streak silhouettes reveal bubble oscillations not shown in the motion pictures. The streak silhouette, Figure 13, shows a large initial cavitation bubble formation appearing less than 0.0002 second after the detonation. The shock wave would be somewhere between 12 and 18 inches from its starting point at the time of the first bubble formation. The bubbles appear in a region extending from 5 inches to more than 10 inches from the point of detonation. This is probably a region of pressure below that of the atmosphere. From this, the pressure-distance curve of Figure 14 is assumed for some time after detonation.

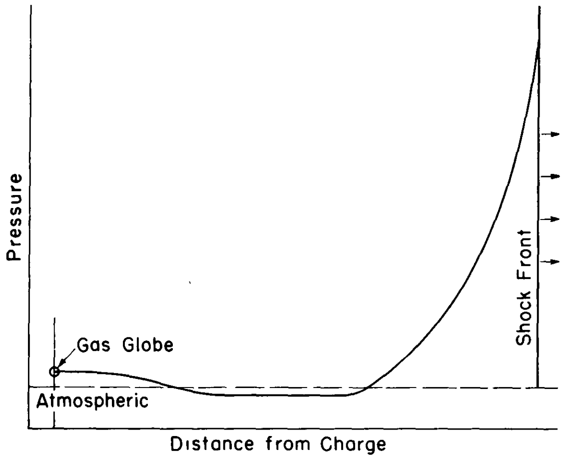

Figure 14 - Schematic Diagram showing Pressure Distribution in the Water Surrounding a Gas Globe at a Given Instant, as suggested by the Formation of Bubbles behind the Shock Wave

The formation of cavitation bubbles appeared to be greater at low pressure, but this is not definite. The air content of the water seemed to have considerable bearing on bubble formation. Two explosions under equal pressure are compared in Figures 15a and 15b. Figure 15a shows the formation of bubbles during an explosion in water which had no particular reduction of air content, and Figure 15b shows an explosion in water which had been allowed to stand overnight under reduced pressure. Small bubbles are seen to form in the frame of Figure 15b immediately following the explosion. None are observed during the remainder of the record.

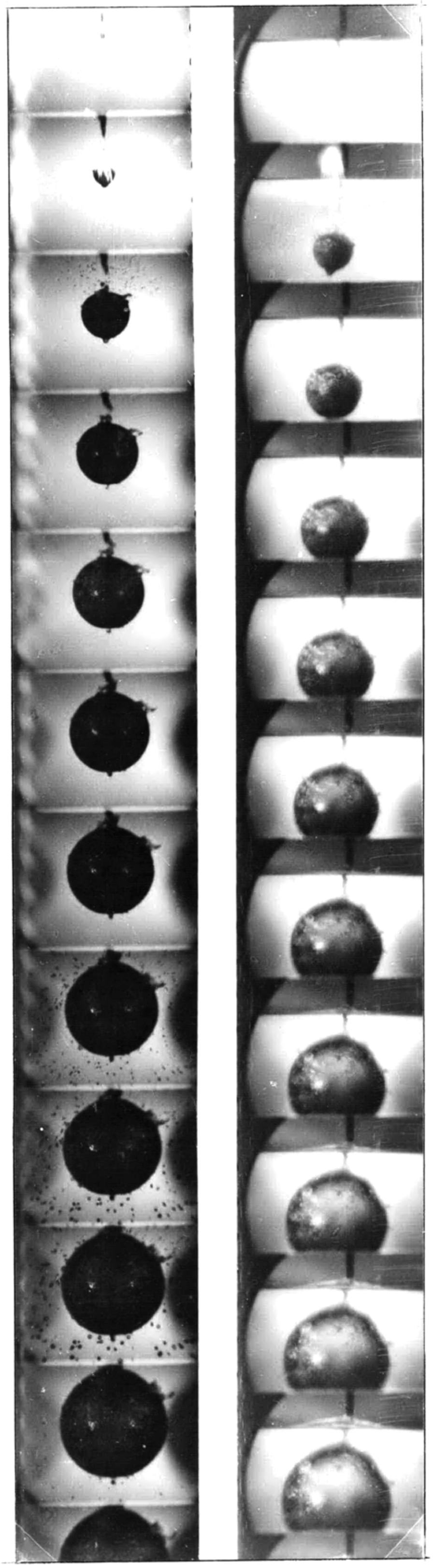

Figure 15a Figure 15b

Figure 15 - Comparison of Two Half-Cap Explosions in Water

The two shots were fired under an absolute pressure of approximately 5 pounds per square inch. The film rate is equal for both explosions, and the arrangement is such that adjoining frames represent the same time after the explosion.

Figure 15a - No attempt was made to reduce the air content of the water for this shot.

Figure 15b - This shot was fired after the water had stood overnight in the tunnel at a reduced pressure of about 2 pounds per square inch. Note the relative absence of bubbles, except in the second frame.

In some records, a peculiar dark-appearing shell was observed to surround the gas globe during some phases of its first expansion, as illustrated by Frames 3, 4, and 5 of Figure 16. It is suggested that this shell may consist of very small cavitation bubbles, or that it may only be caused by the circumstances of lighting, which are not fully understood. This is the first time that such a shell has been noticed and it is possible that it may affect measurements of globe diameter.

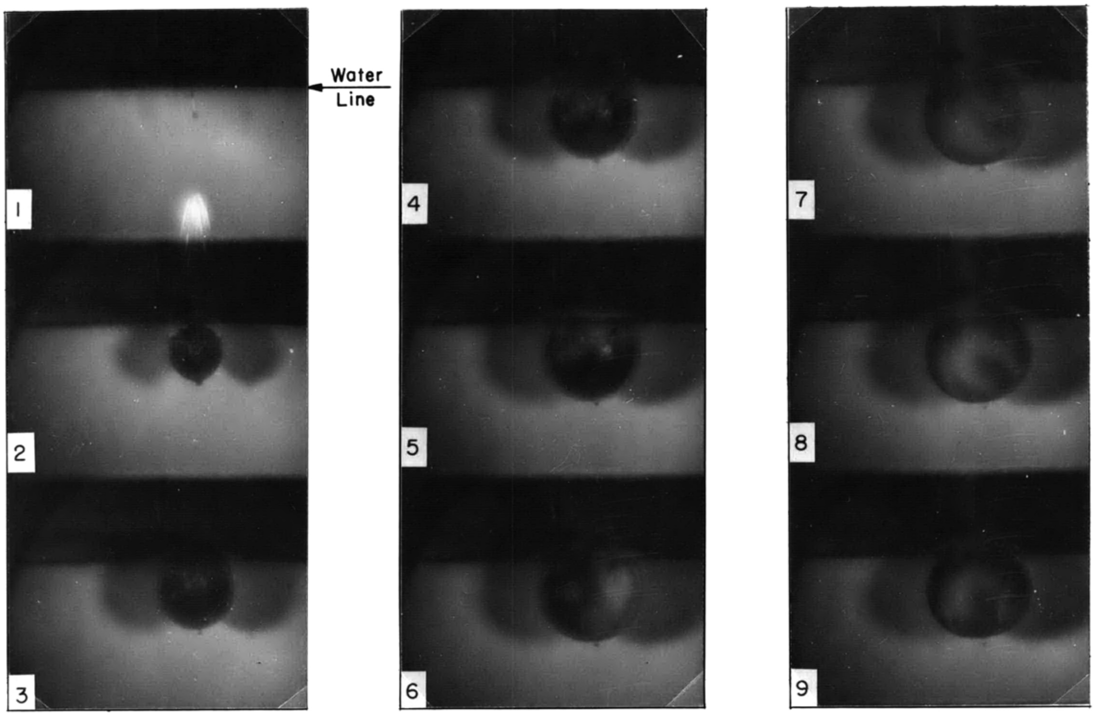

Figure 16 - High-Speed Motion Picture of a Half-Cap Explosion

This explosion occurred 1 inch below the water surface, at atmospheric pressure. A peculiar dark-appearing shell is observed to surround the gas globe in Frames 3, 4, and 5. The diagram of lamps and apparatus for these photographs is shown in Figure 4 on page 5.

At very low pressures the motion pictures show a peculiar phenome- on. The surface is pitted with craters which appear to change shape and attern; the appearance of the outside of the globe almost exactly corre- ponds to the appearance of the under side of the surface of a body of water hen rain is falling on it. Figure 17 depicts this phenomenon.

Pictures showing the action both above and below the water surface ndicate that there is a relationship between motion of the surface dome and ulsation of the gas globe. The section of the motion picture in Figures 18 nd 19 illustrates this point. A clue as to a possible mode of formation of he water plume is shown in Figure 20. Here the globe expands and contracts, nd the surface dome rises and falls. Part way through the contraction phase n air bubble moves downward through the water surface and above it appears he start of the water plume.

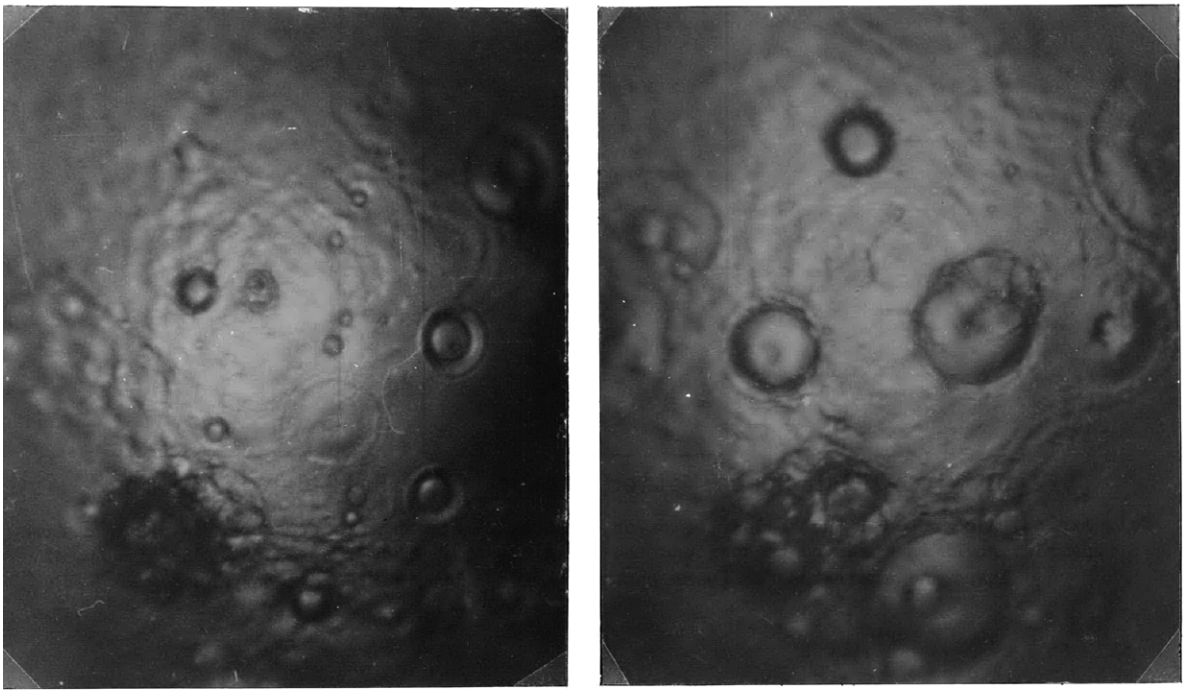

Figure 17a

Figure 17b

Figure 17 - Pattern Observed on the Surface of the Gas Globe produced by the Explosion of a Half-Cap at a Pressure of Approximately 1.0 Pound per Square Inch Absolute

These photographs are obtained from enlarged frames of the same high-speed motion picture. Figure 17b is 0.025 second after Figure 17a.

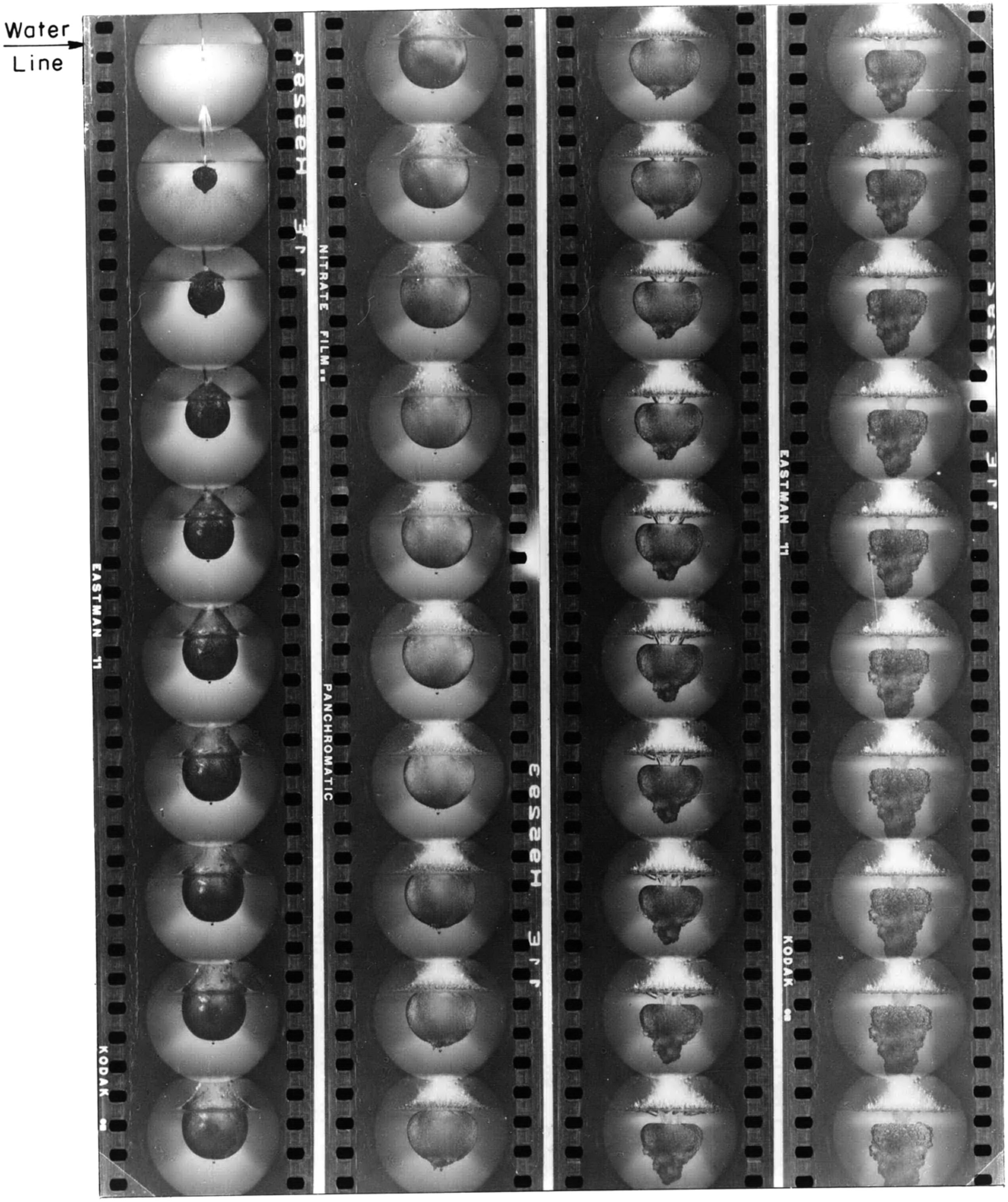

Figure 18 - High-Speed Motion Picture showing the Above-Water and Below-Water Phenomena during an Explosion

This motion picture taken in the 24-inch variable pressure water tunnel shows the action resulting from the explosion of a half-cap 1 1/2 inch below the water surface under a pressure of 5 pounds per square inch. The frame rate is 1080 frames per second. The start of the migration of the gas globe toward the bottom of the water tunnel test section can be seen toward the end of this figure.

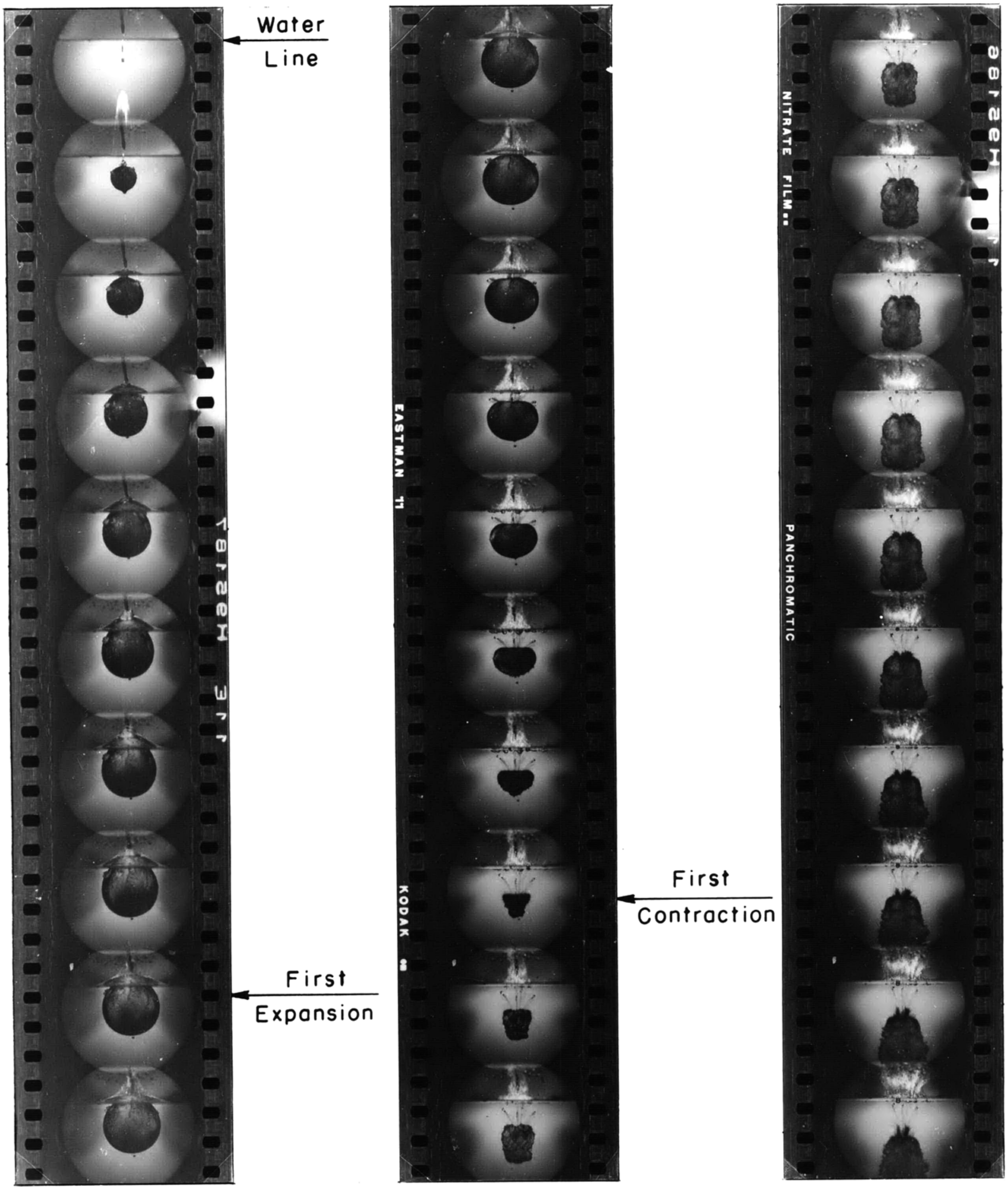

Figure 19 - High-Speed Motion Picture of the Explosion of a Half-Cap

This shows the action, both above and below the water surface, at 1080 frames per second. The cap was submerged to a depth of 1 1/2 inch of water and the absolute pressure at that depth was 10 pounds per square inch.

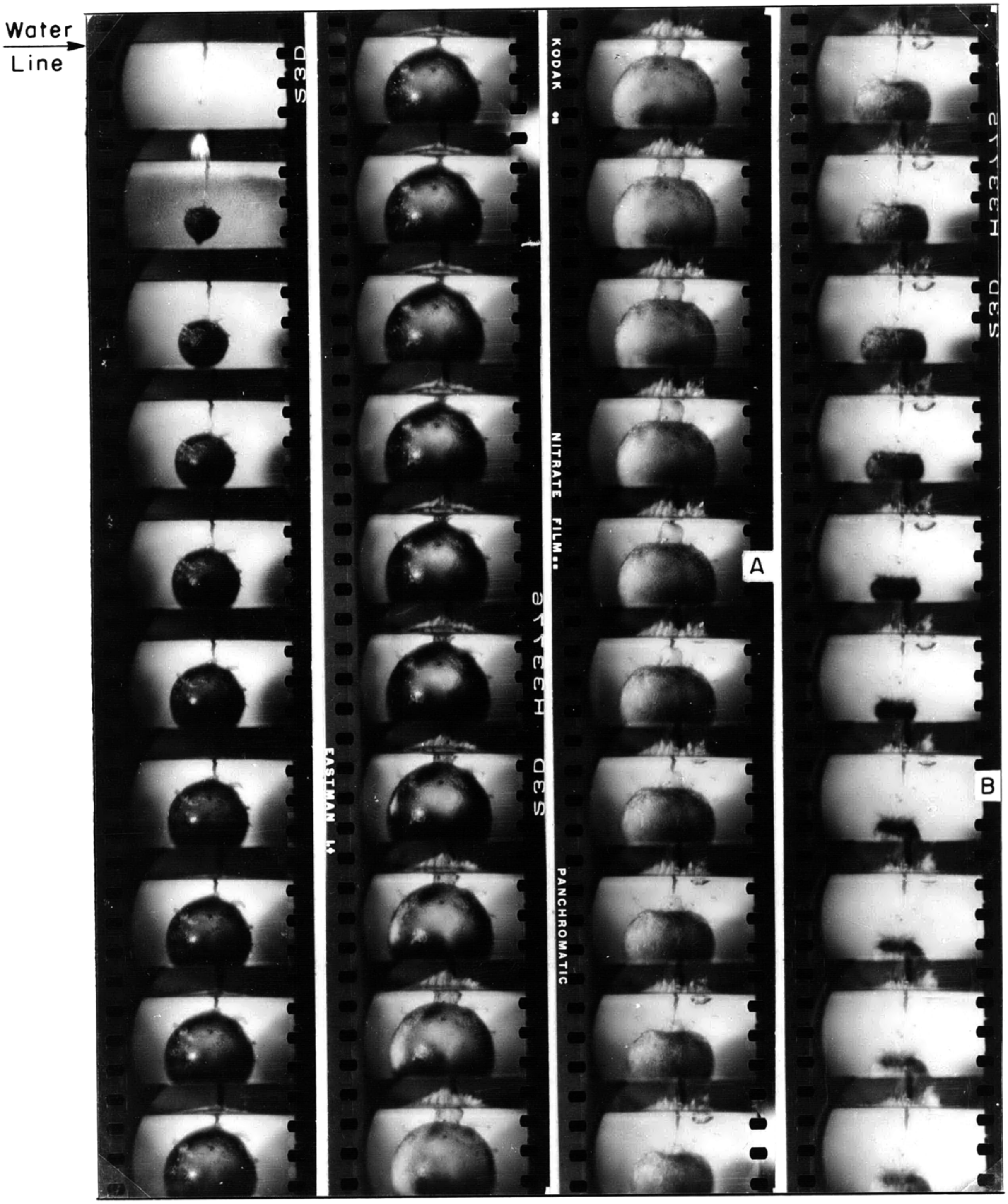

Figure 20 - High-Speed Motion Picture of a Half-Cap Explosion

The cap was placed at a depth of 4 inches of water and at a pressure of 5 pounds per square inch absolute. This picture shows an interesting plume formation. A bubble starts downward through the water surface at A. A plume starts from the water surface above the bubble and at B is fairly well formed. This plume is the basis of the entire plume structure which continues for many milliseconds after the last frame shown here.

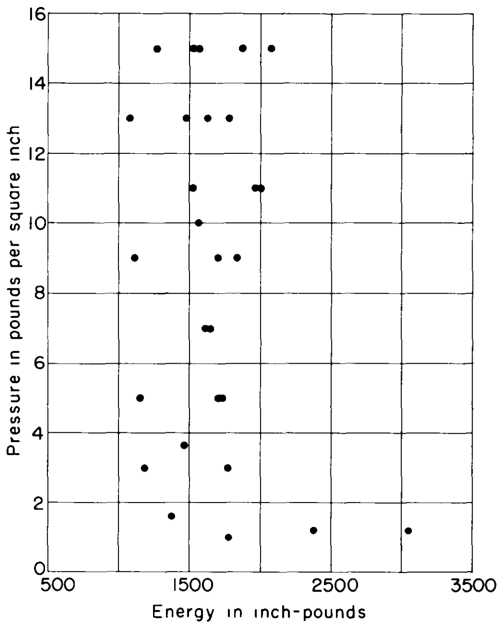

Figure 21 - Plot showing the Energy remaining in a Half-Cap Gas Globe at Maximum Diameter

This energy is the product of the maximum volume and the absolute pressure at the charge.

The value of energy remaining at the point of maximum expansion has been calculated to be in the order of 1370 inch-pounds; see the Appendix.

The energy of globe motion at the point of maximum expansion for the half-caps has been calculated in the Appendix, page 32. From the chemical composition and an assumed chemical reaction it is found to be 1370 inch-pounds. This value should be accurate to within 10 per cent. The energies calculated from the pressure-volume relationship are shown as a function of pressure in Figure 21. These values are in fair agreement with the theoretical value.

Analysis of the data thus obtained reveals a qualitative agreement between Herring's theory (9) and the physical fact. According to the theory the free surface will predominate and the pulse frequency will decrease with increased globe diameter. This is based upon a relatively large charge-surface distance with respect to maximum globe diameter.

From the simplest theory a relationship between pulse period and maximum globe size may be determined (9).

$$T = 1.135\,\rho^{\frac{1}{2}}\,P^{-\frac{5}{6}}\,E^{\frac{1}{3}} \qquad [1]$$

where $T$ is the pulse period,

$P$ is the absolute pressure of the water at a great distance from the globe at the same depth as the center of the globe, and

$E$ is the total energy of the pulsating motion.

Also

$$E = \frac{4}{3}\pi R^3 P \qquad [2]$$

where $R$ is the maximum radius of the gas globe. Eliminating $P$ between Equations [1] and [2] and solving for $T$, we obtain

$$T = CR^{\frac{5}{2}}$$

where $C$ is a constant. This must be modified when the globe is in the vicinity of walls or a free surface. A plot of $C$ as a function of pressure is given in Figure 22. There is considerable scatter among all the values, but a straight line is drawn through the several points taken from the "controlled-air" curves of Figures 10 and 11. It is assumed that the slope of this line represents the wall and surface correction which was not applied. A theoretical value for *C*, calculated to be 0.00098, falls close to the points obtained.

Micro-flash still pictures of the shock waves from half-caps fired under atmospheric pressure and under an absolute pressure of 7 pounds per square inch indicate that pressure has no apparent effect on the magnitude of the wave. Figure 23a shows a shock wave 39 microseconds

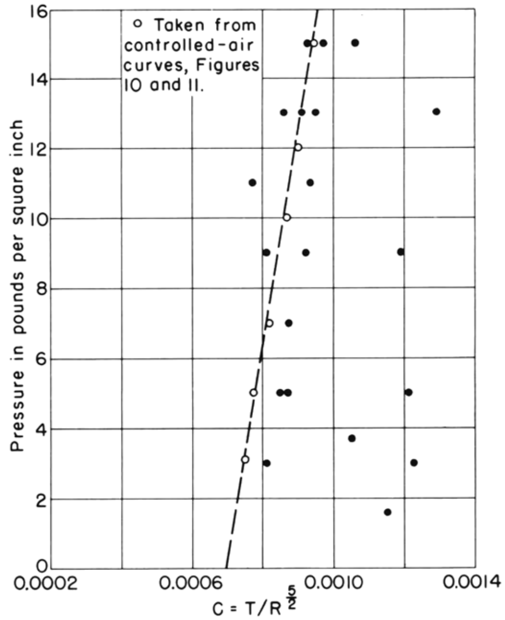

Figure 22 - Plot showing Relationship between *C* and Total Absolute Pressure on the Charge

This is given by $T = CR^{5/2}$, where $T$ is the pulse period, $R$ the maximum globe radius, and $C$ is a constant. $C$ is plotted here as a function of pressure. A theoretical value for $C$ is 0.00098.

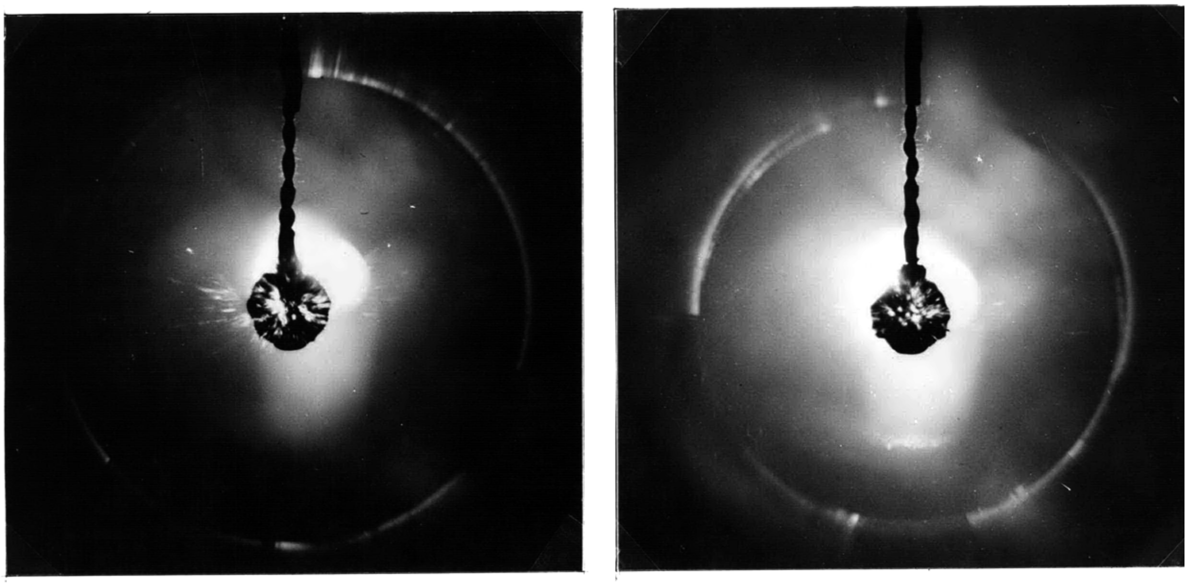

**Figure 23a** - The cap was at a water depth of 6 inches and a pressure of 7 pounds per square inch.

Figure 23b - The cap was at a water depth of 6 inches and at atmospheric pressure.

Figure 23 - Micro-Flash Photograph of a Half-Cap Shock Wave 39 Microseconds after Detonation

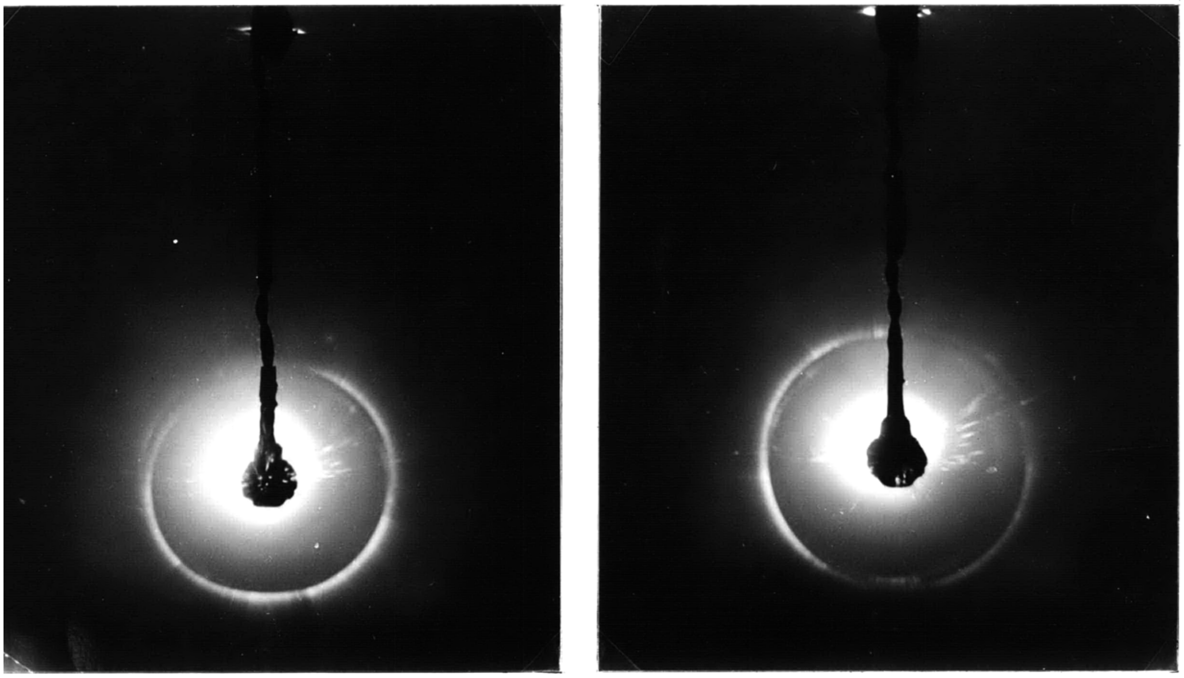

Figure 24a

Figure 24b

Figure 24 - Micro-Flash Photographs of Half-Cap Shock Waves
19 Microseconds after Detonation

The wave form and diameter are reproducible, as is shown with these two half-cap shock explosions.

fter detonation of a half-cap at a depth of water of 6 inches and a pressure f 7 pounds per square inch absolute. Figure 23b shows a shock wave from a alf-cap submerged 6 inches with atmospheric pressure above the surface. The elay after detonation is again 39 microseconds. Inspection of the two pho- ographs, Figures 24a and b, taken with the same time delay after detonation, hows that the waves have reached the same diameter. The wave form in both ases appears to be the same.

The photographs in Figures 25a, b, and c, taken with various time elays after the start of the explosion indicate that the wave remains uni- orm during its propagation.

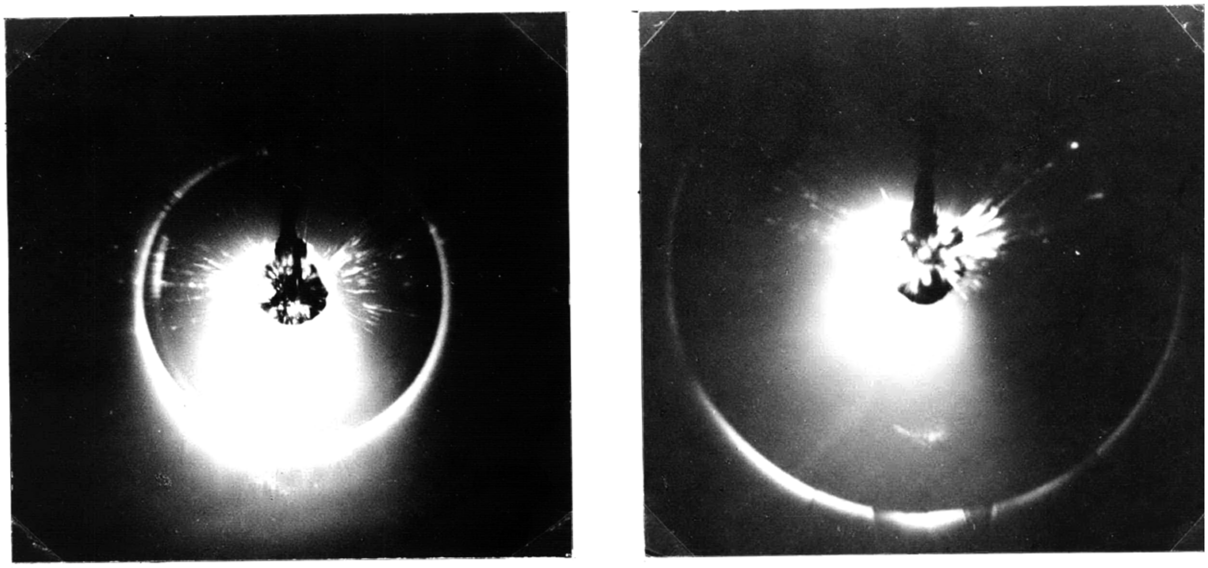

**Figure 25a - 19 microseconds after detonation.**

**Figure 25b - 39 microseconds after detonation.**

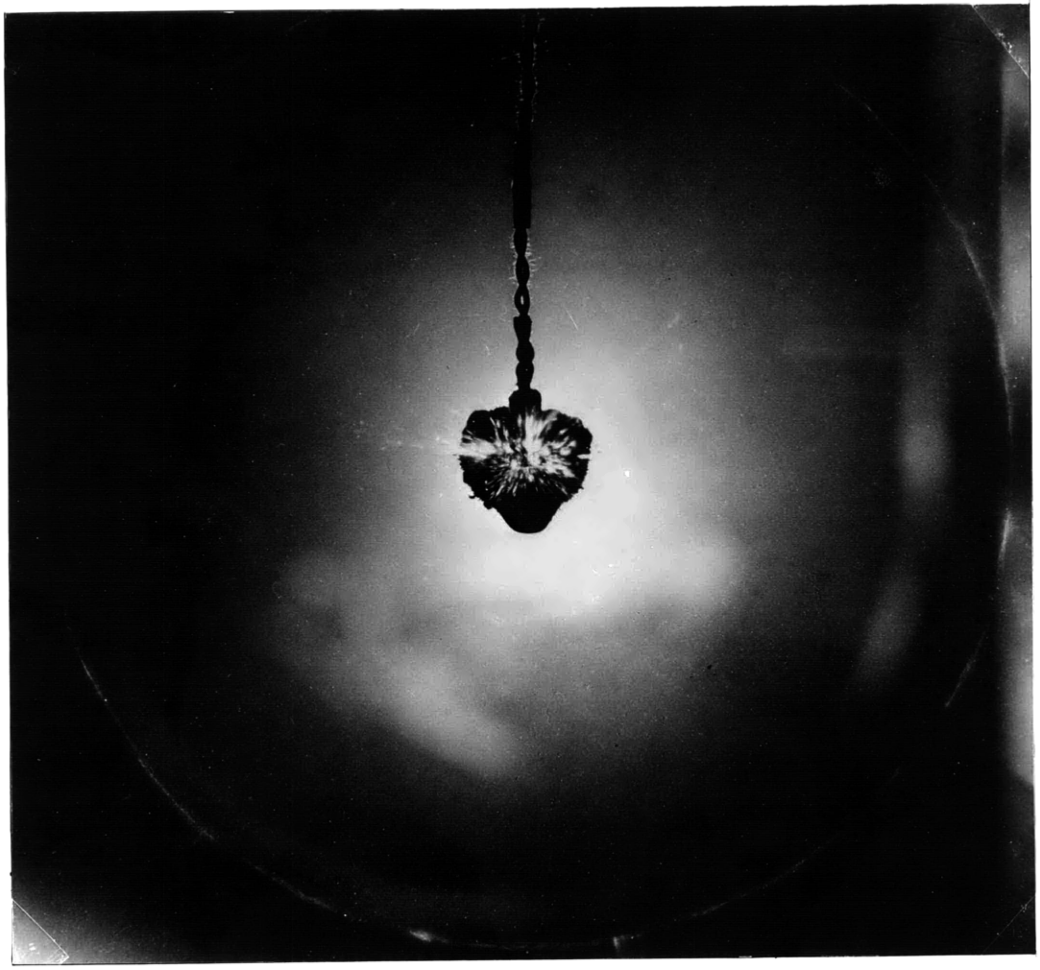

**Figure 25c - 89 microseconds after detonation.**

Figure 25 - Micro-Flash Photographs of Half-Cap Explosions at Various Time Delays

The caps were at a depth of 4 inches with atmospheric pressure on the water surface.

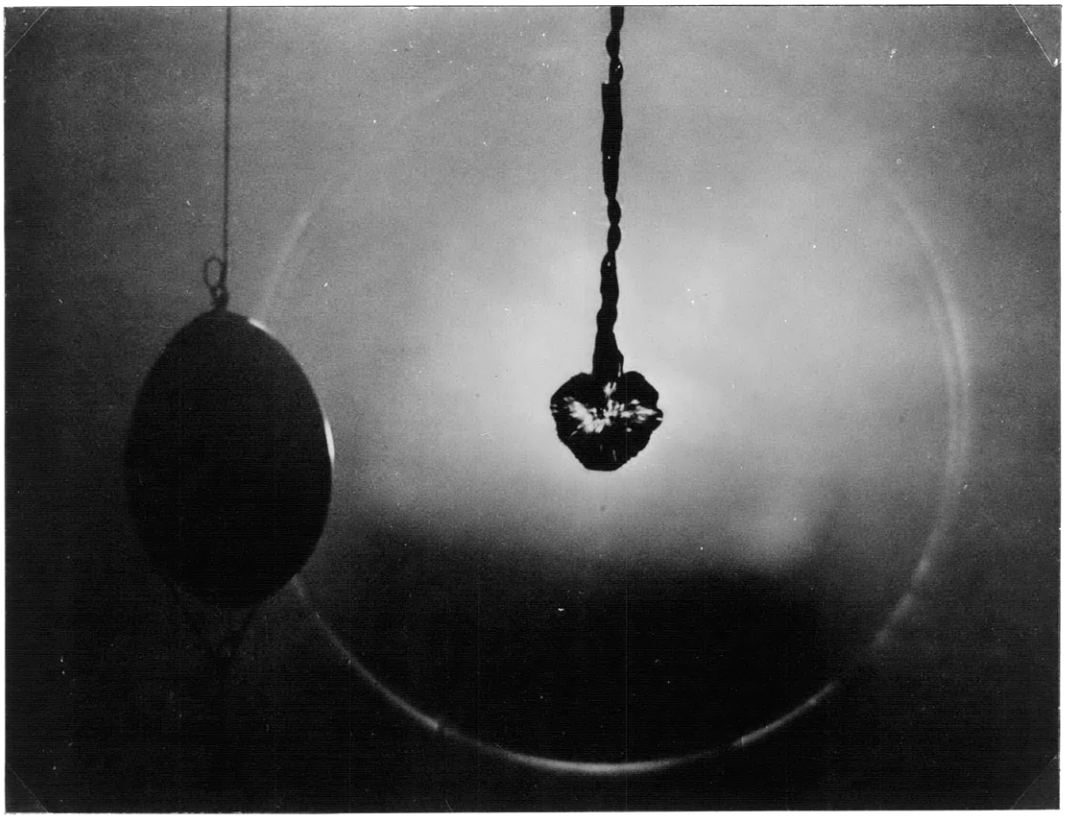

**Figure 26a - 59 microseconds** after detonation. **The wave has traveled 3 1/2 inches.**

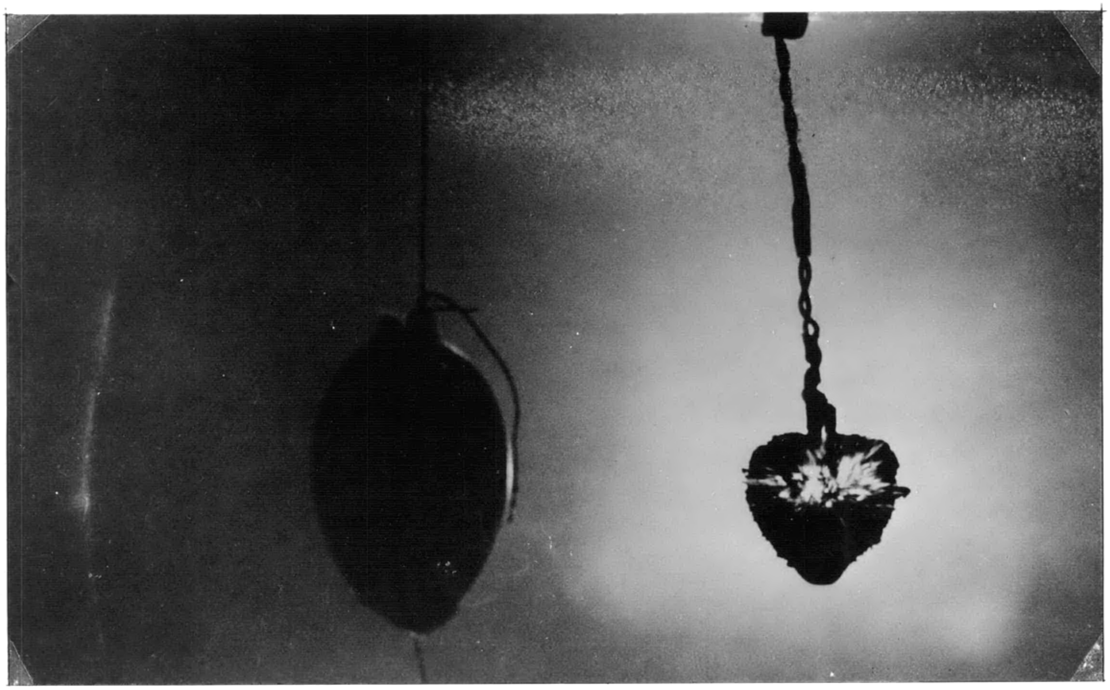

Figure 26b - 119 microseconds after detonation. **The wave has traveled 7 inches.** Note the cavitation bubbles formed behind the shock wave just under the water surface.

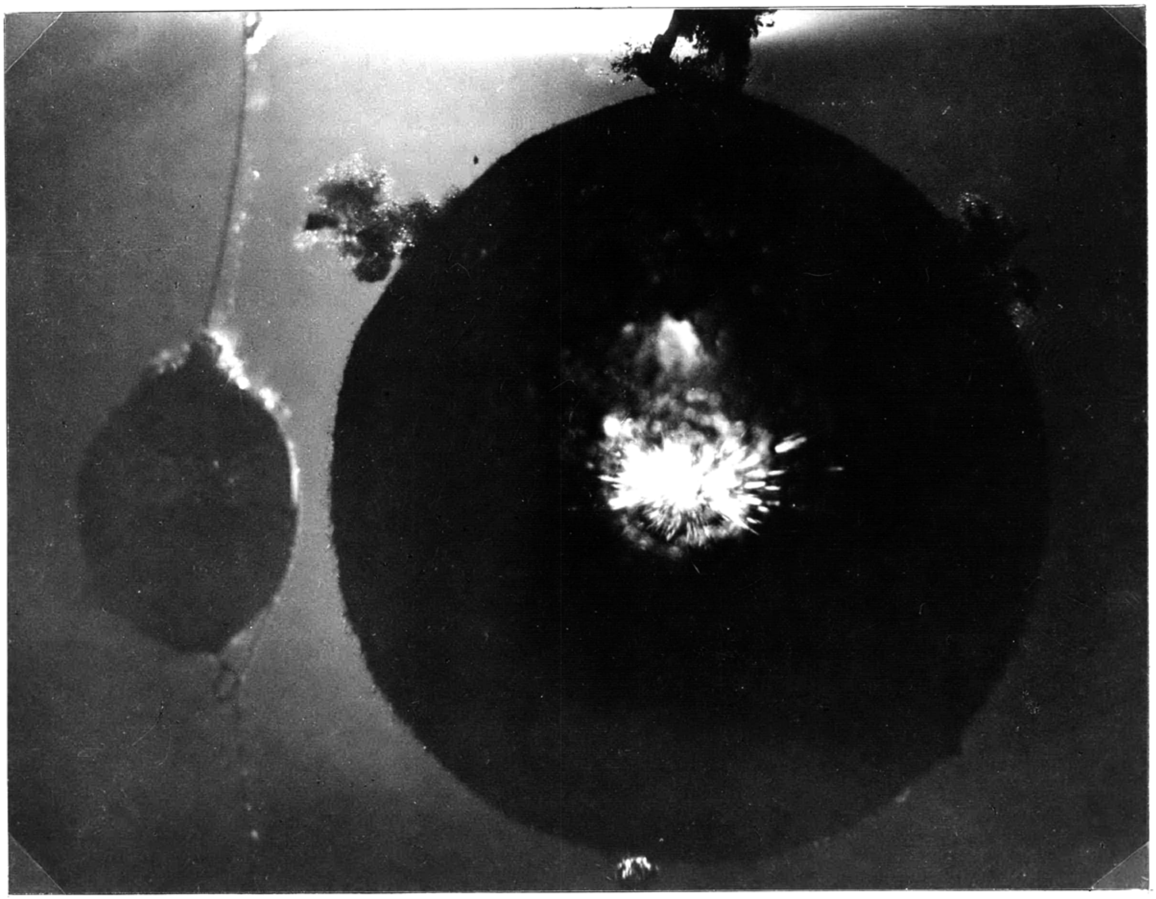

Figure 26c - 5019 microseconds after detonation. Cavitation bubbles may be seen just off the egg and its supporting string. Two protuberances are seen on the upper side of the gas globe.

Figure 26 - Micro-Flash Photographs of Half-Cap Explosions near Air-Filled Egg Shells

Micro-flash photographs of shock waves passing air-filled egg shells do not bring forth any visual evidence of damage to the egg. Figures 26a, b, and c are photographs showing various stages in the travel of the shock wave past the eggs. Figure 26b taken slightly over a hundred microseconds after the start of detonation reveals a rather extensive cavitation field just under the water surface. These bubbles have formed immediately behind the shock wave reflected from the surface. Figure 26c is a micro-flash shot caught near the maximum expansion of the gas globe. Cavitation bubbles may be seen off the egg and its supporting string. Two interesting protuberances may be seen coming from the gas globe. Motion pictures of the eggs reveal visible cracks forming less than 2 milliseconds after detonation. When these motion pictures are projected they show that the air contained in the egg pulsates in sympathy with the gas globe (3).

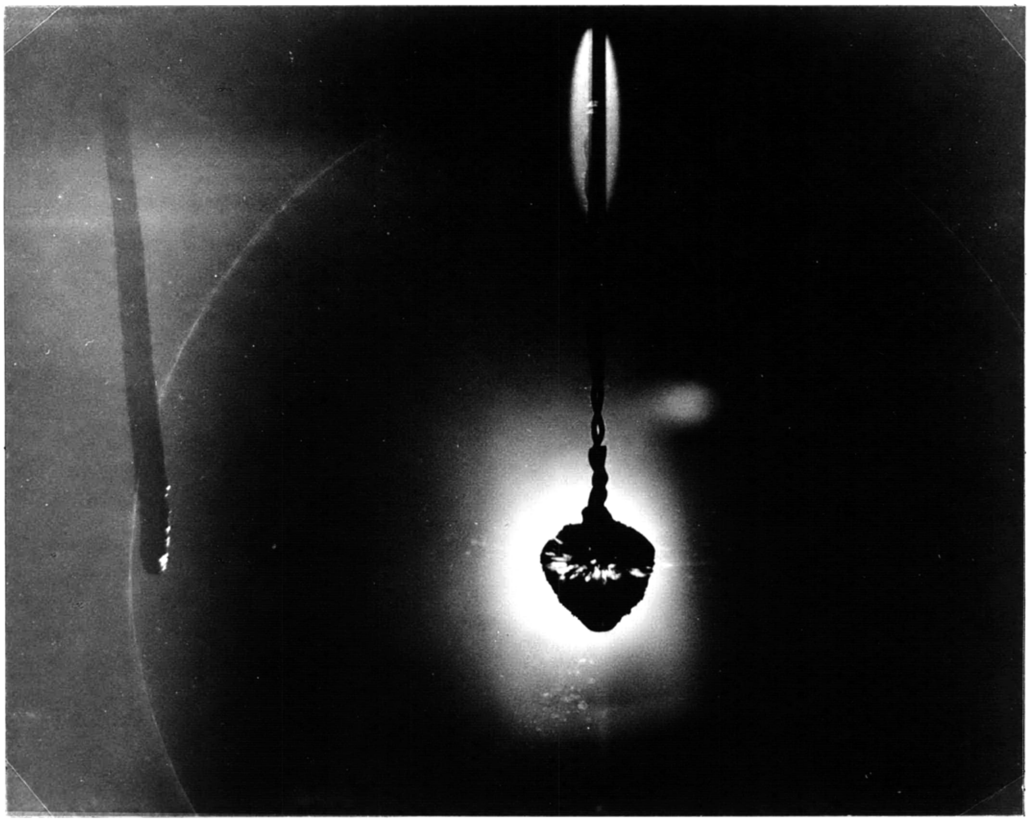

Figure 27a - Micro-Flash Photograph of a Half-Cap Explosion near a Pressure Gage

This photograph taken 82 microseconds after detonation shows the shock wave just past a piezoelectric pressure gage placed 4.6 inches from the charge. The pressure record is reproduced in Figure 27b.

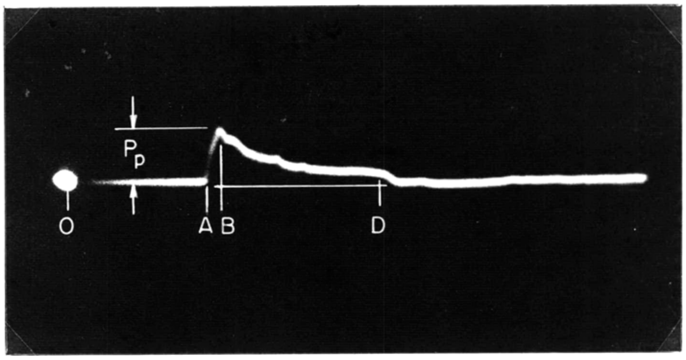

Figure 27b - Pressure Record obtained in the Half-Cap Explosion shown in Figure 27a

$P_p$, Maximum pressure, 576 pounds per square inch

OA, Time of transit, charge to gage, 68 microseconds

AB, Time to rise to peak pressure, 6.7 microseconds

BD, Time to fall approximately 90 per cent of peak, 76 microseconds

To be certain that the phenomenon recorded photographically was the shock wave, the egg was replaced by a piezoelectric gage and oscillographic pressure records were obtained. The photographic shock wave was found to correspond to the peak pressure at that given instant and position. Figure 27b shows the oscillograph record obtained for the half-cap explosion in Figure 27a.

## CONCLUSIONS

The photographs and data presented in this paper are self-explanatory. Exact similitude with full-scale explosions cannot be assumed, however, both because of variations in the total pressure against which the gas globe expands (1) and because, on this small scale, the motion is affected by the boundaries of the chamber in which the tests were made (10).

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(2) "Underwater Explosion Phenomena," TMB CONFIDENTIAL Motion Picture, February 1943.

(3) "Small-Scale Underwater Explosions under Reduced Atmospheric Pressure," TMB CONFIDENTIAL Motion Picture, film in preparation.

(4) TMB CONFIDENTIAL letter C-S85-2 of 17 August 1942 to Coordinator of Research and Development, Navy Department, describing high-speed photographic equipment.

(5) "Photographic Studies of Shock Waves in Water," by Lt. D.C. Campbell, USNR, TMB CONFIDENTIAL Report R-77, November 1942.

(6) "Experiments in the Production and Photography of Intersecting Underwater Shock Waves," by Lt. D.C. Campbell, USNR, TMB CONFIDENTIAL Report R-203, September 1943.

(7) "A Microsecond Time-Delay Trigger Circuit," by Lt. G.R. Mezger, USNR, TMB Report 525, to be published.

(8) "A Rubber-Coated Tourmaline Crystal Gage," by A.R. Cohen and B. Stiller, TMB Report R-157, to be published.

(9) "Theory of the Pulsations of the Gas Globe Produced by an Underwater Explosion," by Conyers Herring, National Defense Research Committee CONFIDENTIAL Report C4-sr 20-010, October 1941.

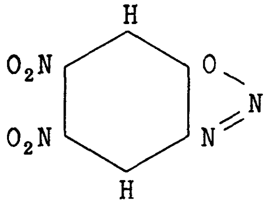
(10) "Migration of Underwater Gas Globes due to Gravity and Neighboring Surfaces," by E.H. Kennard, TMB CONFIDENTIAL Report R-182, to be published.

## APPENDIX

## CALCULATION OF GLOBE ENERGY FROM KNOWN CHEMICAL FORMULA

The Hercules ND-24 cannon primer (half-cap) contains 0.09 gram of

75 per cent diazodinitrophenol $C_6H_2N_4O_5$



25 per cent potassium chlorate $KClO_3$

The molecular weights are 210 and 123 respectively.
The reaction is assumed

$$3C_6H_2N_4O_5 + 4KClO_3 \rightarrow 4KCl + 6CO_2 + 12CO + 3H_2O + 6N_2 \qquad [3]$$

The heats of formation are:

| | |
|---|---|
| $C_6H_2N_4O_5$ | unknown |
| $KClO_3$ | 89.9 kg cal/mol |
| KCl | 104.3 kg cal/mol |
| $CO_2$ | 94.4 kg cal/mol (STP) |
| CO | 26.4 kg cal/mol (STP) |
| $H_2O$ | 68.4 kg cal/mol (liquid water) |
| $N_2$ | 0 |

Since the heat of formation of $C_6H_2N_4O_5$ is unknown we will endeavor to determine it from an assumed heat of combustion. Picric Acid $C_6H_3N_3O_7$ has a heat of combustion of 621.2 kg cal/mol, and since the two compounds are very similar it will be assumed that the heat of combustion of $C_6H_2N_4O_5$ is 620 kg cal/mol. The combustion reaction:

$$C_6H_2N_4O_5 + 4O_2 \rightarrow 6CO_2 + H_2O + 2N_2 \qquad [4]$$

the heat of formation:

| | | |
|---|---|---|
| $CO_2$ | 94.4 kg cal/mol x 6 mol = | 566.4 kg cal |
| $H_2O$ | 68.4 kg cal/mol x 1 mol = | 68.4 kg cal |
| $N_2$ | 0 | |
| | Total heat of formation of products of combustion | 634.8 kg cal |

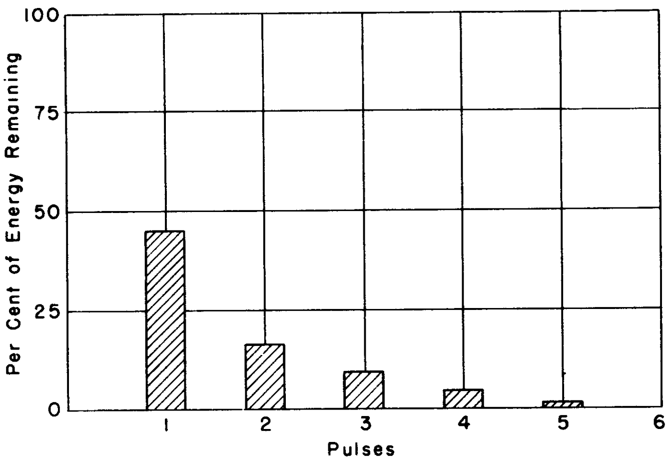


Figure 28 - Typical Energy Dissipation

This diagram is taken from Figure 12 of TMB Report 512. The shaded areas for the pulses are taken at the point of maximum expansion.

And since the heat of formation of a compound A is equal to the sum of the heats of formation of the products of combustion minus the heat of combustion of Compound A

620 - 634.8 = approximately 0 for the heat of formation of $C_6H_2N_4O_5$

Returning to the heats of formation in Reaction [3]

| | |
|---|---|
| KCl yields | 420 kg cal |
| $CO_2$ yields | 570 kg cal |
| CO yields | 320 kg cal |
| $H_2O$ yields | 200 kg cal |
| products of explosion | 1510 kg cal |
| less $KClO_3$ | 360 kg cal |
| | 1150 kg cal net energy of reaction |

The total weight = 3 x 210 + 4 x 123 = 1122 grams

The energy per gram of explosive = $\frac{1150}{1122}$ = 1.03 kg cal/gm

The total energy per half-cap is thus 0.09 gm x 1.03 kg cal/gm = 0.0927 kg cal.

From Figure 28 we may take 40 per cent as the energy which goes into the gas globe:

0.40 x 0.0927 = 0.037 kg cal

As 1 kg cal = 3087 x 12 inch-pounds, the gas globe energy is 1370 inch-pounds.