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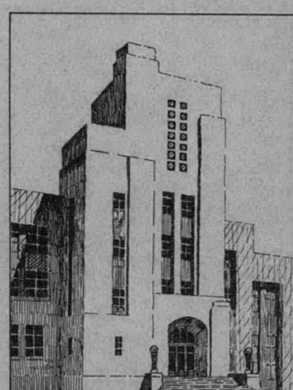
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

MOTIONS OF A PULSATING GAS GLOBE UNDER WATER

A PHOTOGRAPHIC STUDY

BY LT. D. C. CAMPBELL, USNR



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NAVY DEPARTMENT

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WASHINGTON, D.C.

REPORT 512

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PERSONNEL

The experiments described herein were conducted at the David W. Taylor Model Basin by Dr. C.W. Wyckoff and Lieutenant D.C. Campbell, USNR. The report was written by Lieutenant Campbell.

MOTIONS OF A PULSATING GAS GLOBE UNDER WATER
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ABSTRACT

High-speed motion pictures (1)* of small underwater explosions were made under laboratory conditions. Enlargements of selected frames in several of these series are reproduced to show the pulsations of the gas globe and the influence of boundary surfaces on its motion. The shock wave does not appear in the photographs. Data obtained from the photographs are plotted and the results are analyzed in terms of diameter as a function of time, of period, and of migration of the globe.

INTRODUCTION

The design of ship structures to withstand explosive loading requires an understanding of the nature of this loading. In the course of an extended study of the action of underwater explosions (2) a series of high-speed motion pictures have been made at the David W. Taylor Model Basin of the gas globe produced by small-scale explosions. There is doubt as to whether these results, if stepped up to full scale, would correspond to those produced by the explosion of large charges in mines and torpedoes, but the data are suggestive and have qualitative validity.

For some time, submarine personnel have noticed that more than one impact results from a single nearby underwater explosion, such as a depth charge. Successive shocks were noted, and it was believed that the intensity and the time between blows decreased with each successive blow. Motion pictures of the action of floating models subjected to underwater explosions corroborated this impression; they revealed that the model received several impacts from the explosion of a single charge (3). Some theoretical investigations have been made in England (4) and in the United States (5) which indicate pulsations and movements of the globe of gas caused by the products of the explosion.

Five different conditions were studied by the photographic method used at the David W. Taylor Model Basin:

1. The first group of pictures were taken in water in a model basin, at fairly large distances from the surrounding walls and bottom. They were intended to show the free pulsations and any effect which might be produced by varying the depth of the charge below the water surface.

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* Numbers in parentheses indicate references on page 64 of this report.

2. In the second group, charges fired at various distances from a rigid vertical wall of concrete were photographed for migration and for pulse frequency.

3. The third series of shots were fired beneath a flat-bottomed raft or boat for comparison with those fired in the free-surface condition.

4. The fourth group was taken to show the globe migration toward a rigid bottom, for charges placed at various distances above the bottom.

5. A study of the effect of placing the charge midway between two vertical parallel plates of steel is given in the last group of photographs.

Approximately 80,000 frames of motion picture film have been analyzed up to the time of the present writing. Representative pictures and the data derived from their analysis are reproduced in this report.

TEST APPARATUS AND PROCEDURE

The photographic equipment used was the high-speed stroboscopic motion picture camera developed by Edgerton (6). A 100-foot strip of 35mm Plus X motion picture film was used on each shot. From 50 to 100 per cent overdevelopment in the contrasty developer "D-11" was necessary to bring out the underexposed images. Lamps which gave an extremely intense flash of light for a very short duration were employed for illumination. The lamps flashed in synchronism with the frame frequency of the motion picture camera. Most of the exposures were made at about 1500 frames per second. The frame speed was indicated by small dots left on the edge of the film by a 60-cycle high-tension spark.

Many difficulties were encountered in obtaining the pictures under water. The first attempts were made in the high-speed model basin where it was found that impurities in the water absorbed and diffused so much light that there was very little image left on the film. To minimize the various losses of light, the project was moved to the small model basin where clean filtered water from the drinking water system could be used and readily renewed. Watertight lamp housings with plastic windows were constructed so that the light source could be brought very close to the area being photographed.

The arrangements used are shown in Figures 1 to 5. A waterscope with a plastic window was placed through the water surface to reduce the loss of light at the air-water interface. A common plate-glass mirror hanging beneath the waterscope was used to direct the horizontal light from the photographic area vertically into the waterscope and the camera. The mirror was placed near the area to be photographed and the distance necessary to get the image on the film was made up in the air space between the camera and the waterscope. The mirror and the underwater lamps were broken when placed too close to the explosion. This rendered it difficult to secure sufficient light and yet to avoid damage to the equipment.

A similar arrangement was used throughout, except that for the fifth group of experiments in which charges were exploded between parallel plates, a bulkhead was built 4 feet from the west end of the small model basin, as shown in Figure 5. In the center of the bulkhead, 36 inches from the bottom and 32 inches from the water surface, was placed a glass window 10 inches in diameter. Underwater photography through this window, from the dry space at the end of the basin, was relatively simple. Illumination was provided by the underwater lamps, as before.

Detailed dispositions in the several series were as follows:

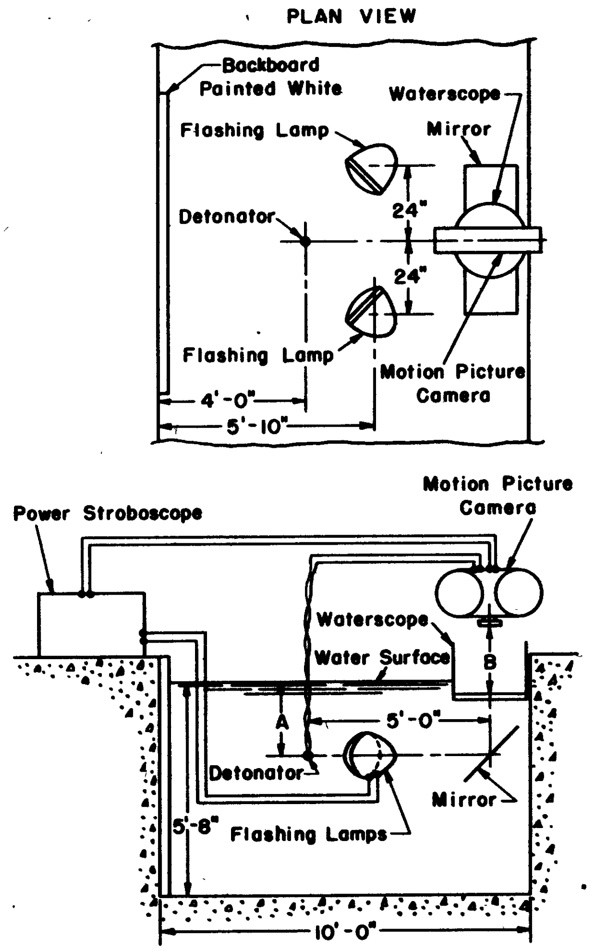


Figure 1 - Setup used to obtain Photographs in Series 1, Figures 6, 7, and 8

The depth *A* of the charge and the height *B* of the camera are variable distances. The underwater lamps were housed in watertight boxes.

1. Explosions in Free Water

The first series of shots were fired in water 5 feet 8 inches deep at the west end of the small model basin. The caps were fired at 36, 24, and 12 inches below the water surface and 48 inches from the nearest side wall, which is distant enough to reduce interference to a negligible amount. Figure 1 indicates schematically the arrangement of various pieces of equipment.

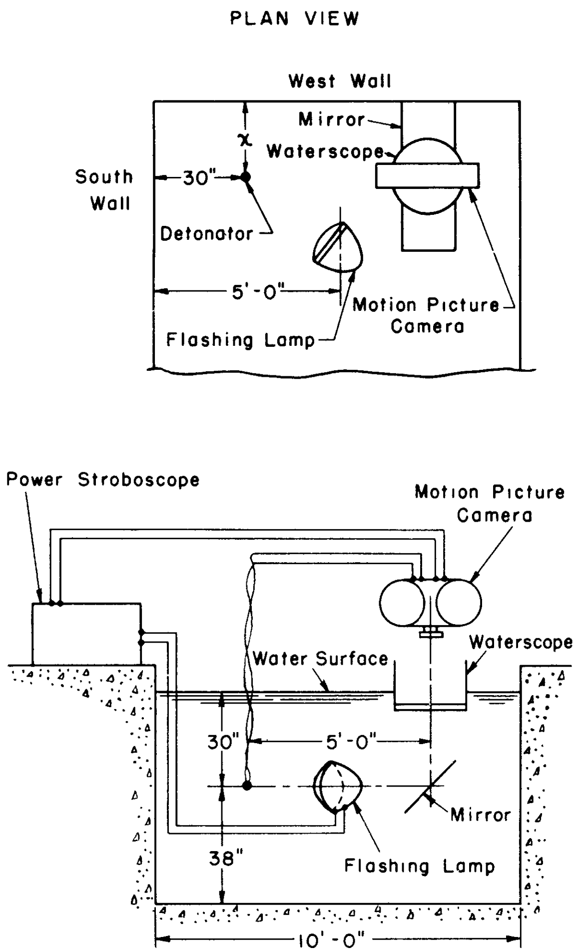


Figure 2 - Setup used to obtain Photographs in Series 2, Figures 14 to 19

The distance *x* from the west wall is variable. With this arrangement, directions in the photographs are reversed, because the camera is photographing an image of the explosion in the mirror, not the explosion itself.

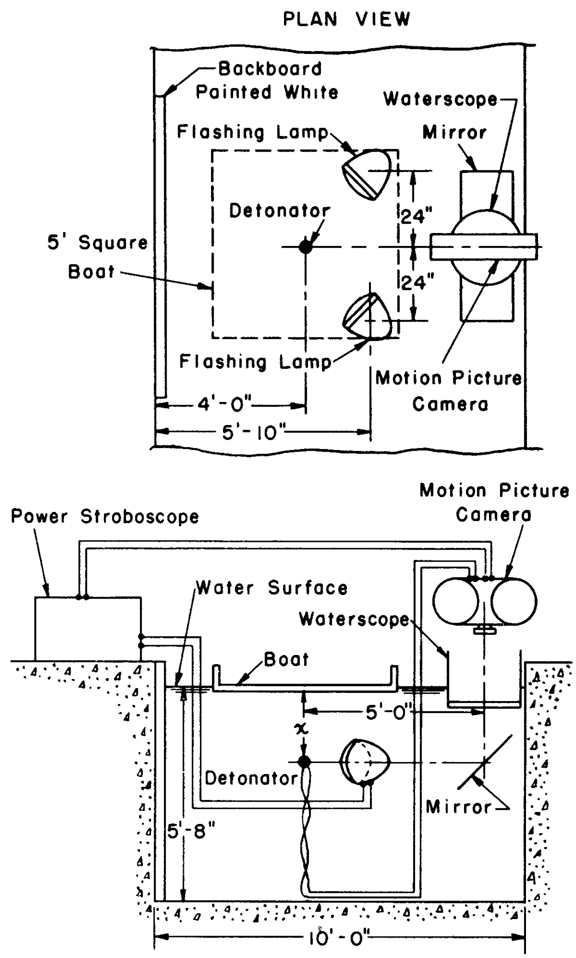


Figure 3 - Setup used to obtain Photographs in Series 3, Figures 22 and 23

The distance *x* from the boat is variable.

2. Explosions Near a Vertical Wall

The second series of shots were fired at a depth of 30 inches in the southwest corner of the small model basin. The charge was placed 30 inches from the south wall and at 24, 18, 12, 9, 6, 3, and 0 inches from the west wall. A diagram showing the arrangement of equipment is given in Figure 2.

3. Explosions Under a Raft or a Boat

Five shots were fired under a boat at depths of 24, 18, 12, 6, and 0 inches. The boat was 5 feet square and flat-bottomed. The bottom was made of 2-inch plank and covered with 1/16-inch steel sheet. The sides were 2-inch

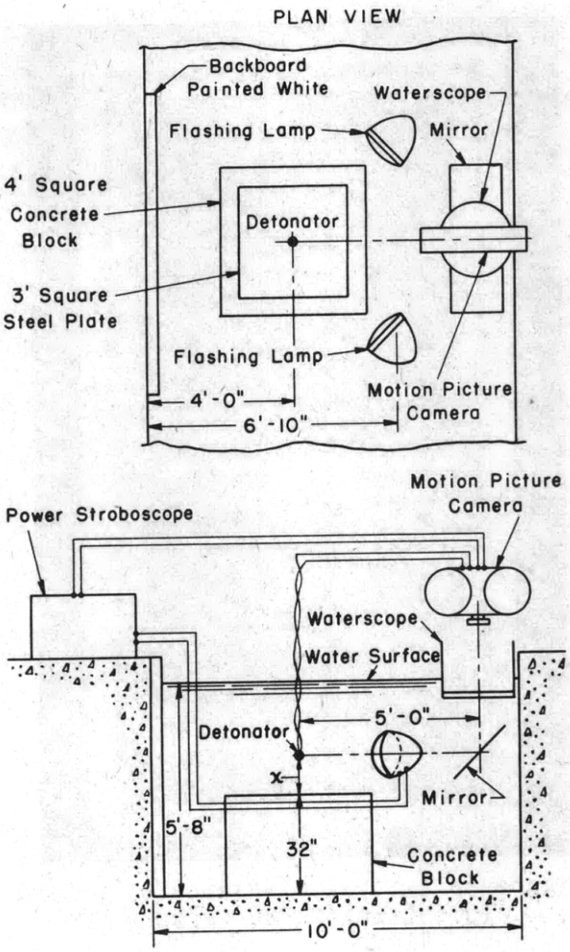


Figure 4a - Setup used to obtain Photographs in Series 4, Figures 26 to 29 and 31

The distance *x* above the bottom is variable.

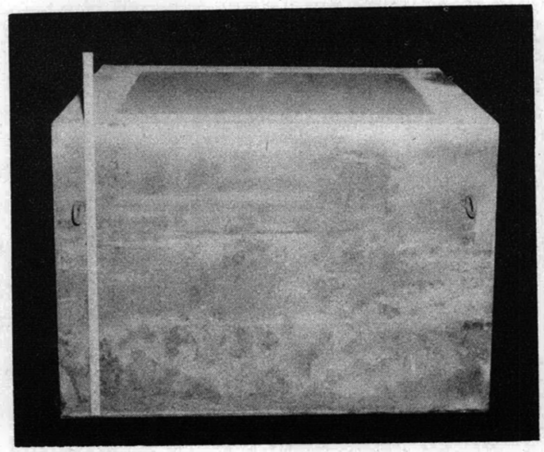


Figure 4b - Concrete Block used as a False Bottom for making the Photographs, Figures 26 to 29 and 31

A steel plate 36 inches square and 1/2 inch thick was cast into the top of the block.

planks which extended 6 inches above the bottom. The weight dry was 183 pounds. When floating the boat drew roughly one inch of water.

The setup of equipment is shown in Figure 3. In this case the charge was supported from the bottom of the basin.

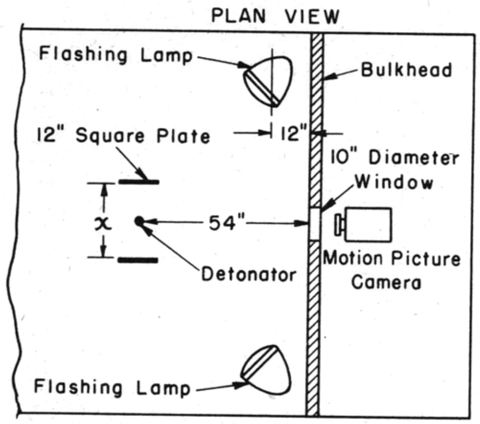
4. Explosions Near a Bottom

A concrete block 4 feet square and 32 inches high was placed in the bottom of the small model basin, as shown in Figure 4a. Cast into the top of this concrete block was a 1/2-inch steel plate 3 feet square which served as the bottom in this series of experiments, Figure 4b. The depth of water in the basin was 5 feet 8 inches, which left 36 inches of water over the block.

The charges were exploded at depths of 1, 3, 18, 25 1/2, and 36 inches below the surface, at clearances from the bottom of 35, 33, 18, 10 1/2, and 0 inches.

5. Explosions Between Parallel Plates

The last group of photographs was made with the parallel-plate set-up shown in Figure 5a. Two steel plates 12 inches square and 1/2 inch thick



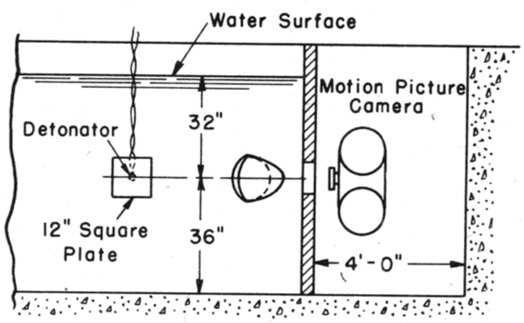


Figure 5a - Setup used to obtain Photographs in Series 5, Figures 33 and 34

The distance *x* between the plates is variable.

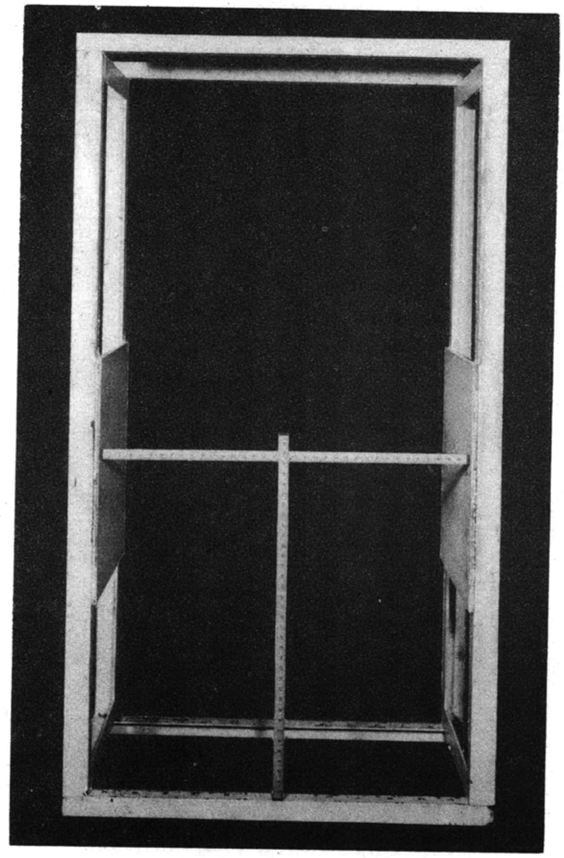


Figure 5b - Parallel-Plate Setup used in obtaining Photographs, Figures 33 and 34

were welded to a steel framework; the side frames were so arranged that the distance between the plates could be varied, as shown in Figure 5b.

With the centers of the plates at a 36-inch depth in 5 feet 8 inches of water, 6 charges were fired, with the plates 36, 30, 24, 18, 12, and 6 inches apart. The charge was in each case midway between the two plates.

CHARGES

Most of the charges used in this investigation were standard Dupont Number 8 electric blasting caps. Externally they are about 1/4 inch in diameter and 2 inches long. The contents are roughly equivalent to 1/2 gram of tetryl, but in view of the wholly different nature of the explosives in the two cases, this equivalence is doubtful. Once the gas globe is formed, however, and the hydrodynamic action begins, the most pertinent question refers to the quantity of energy evolved. Though the volume of gas is of secondary importance it has been measured, and the value obtained at room temperature and pressure is 16 cubic inches for the Number 8 cap.

One Mark 1, Modification 1, mine detonator was used which contained 65 grains of fulminate of mercury; this is roughly the equivalent of 1 gram of tetryl. One 13.3-gram charge of tetryl was also used.

The charges were fired electrically by a time-delay mechanism attached to the camera. The camera was started, and after it had reached the proper speed the firing circuit was automatically closed.

TEST RESULTS

Enlargements of representative pictures are reproduced on pages 8 to 13, 18 to 29, 34 to 37, 42 to 49, 52 to 55, and 58 to 61. The complete motion picture films (1) when projected show the pulsations of the gas globe and its movement toward a rigid surface in a startlingly graphical manner.

Frame-by-frame analyses of these motions were obtained by measurements on the screen of a microfilm reader. Scales placed in the photographic area and photographed subsequent to the actual explosion test were used to convert the readings to full size. Results of these measurements are given in the discussion which follows.

DISCUSSION OF RESULTS

1. Explosions in Free Water

An enormous initial pressure is produced at the instant of detonation. It is estimated to be of the order of 10^5 atmospheres. This pressure dispatches the shock wave and imparts a high momentum to the water and in doing so drops abruptly to about 1/3 of this value. The shock wave is shown in other pictures separately reported (7). Because of the high momentum the globe expands radially outward with an initial velocity greater than that of solid projectiles fired from a gun. It then overshoots and travels beyond the point at which the gas pressure equals the absolute hydrostatic head of the surrounding water and atmosphere. Eventually, however, the hydrostatic pressure of the water brings the expansion to a halt, and when the pressure in the interior of the globe has been reduced to approximately 1/40 atmosphere, reversed flow inward sets in. The pressure increases as the size of the globe diminishes, but the motion again overshoots, and at the point of extreme compression the pressure again reaches a high peak estimated at around 2500 atmospheres; another shock wave may be sent on its way but if so it has reduced intensity; the cycle of expansion and compression is then repeated, in gradually diminishing intensity, until all the energy of motion is dissipated.

Figures 6, 7, and 8, on pages 8 to 13, show that the gas globe from a Number 8 blasting cap expands first to a maximum diameter of approximately

(Text continued on page 14)

1

A Number 8 blasting cap in free water 36 inches below the surface.

2

The flash of detonation appears above the gas globe; it shows in the picture because the camera has no shutter and uses continuously moving film. This frame was exposed 0.00006 second after the flash.

3

0.0007 second after the flash. The tuft of gas at the bottom can be followed throughout.

4

0.0013 second after the flash.

5

0.0020 second after the flash.

6

0.0026 second after the flash.

7

0.0032 second after the flash. The pictures thus far are successive frames.

8

0.0045 second after the flash. The frame at 0.0038 second and alternate frames from here on are omitted.

9

0.0058 second after the flash.

10

0.0070 second after the flash.

11

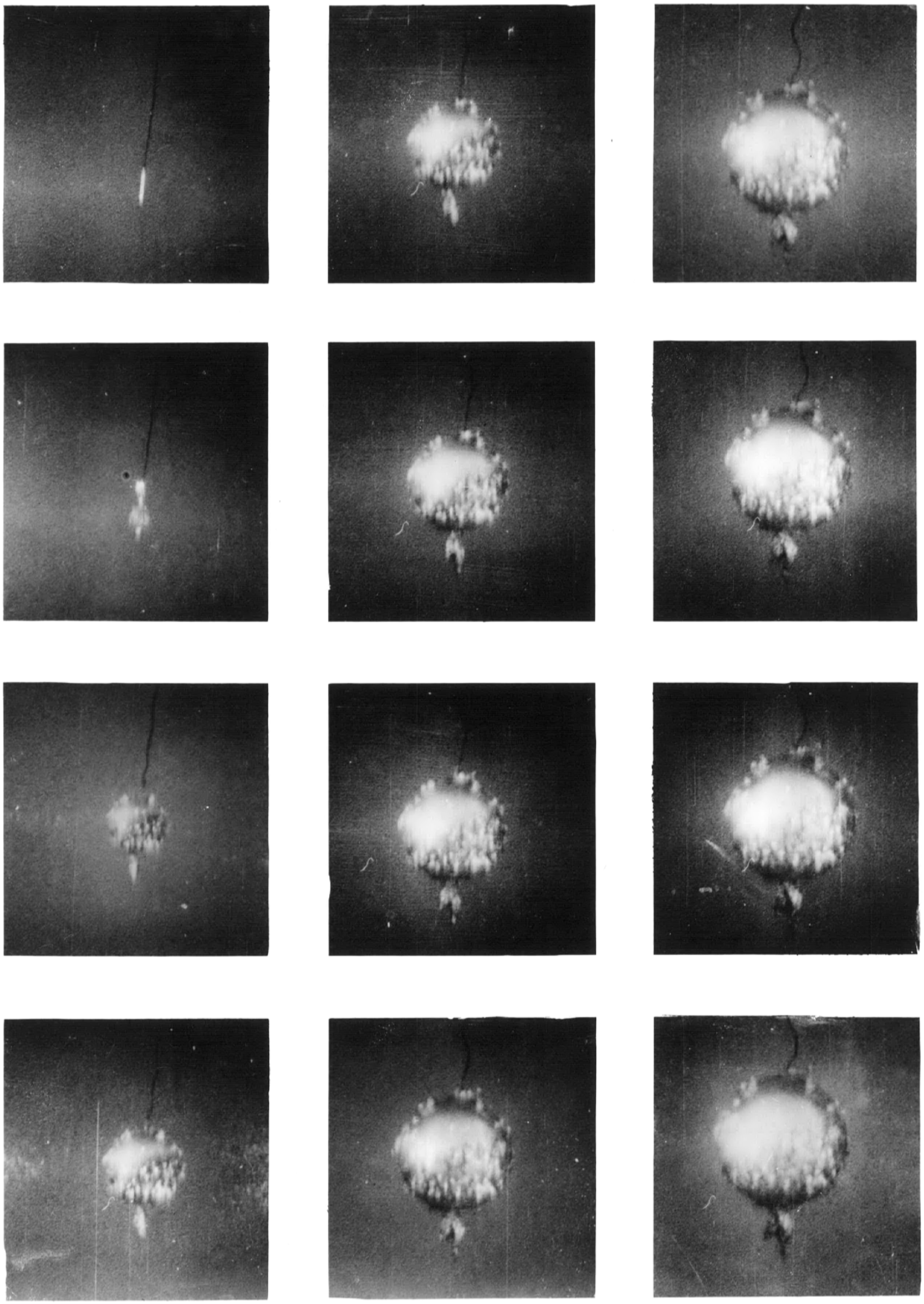
0.0083 second after the flash.

12

0.0096 second after the flash. Maximum diameter of globe, 11 inches. Estimated internal pressure, less than 1/20 atmosphere.

Figure 6 - High-Speed Photographs of a Pulsating Gas Globe

The charge was at a depth of 36 inches. These views and those of Figures 7 and 8 are in some cases not consecutive frames of the motion picture, but were selected as most illustrative of the action of the globe.



1

0.0108 second after the flash. The next two frames are omitted.

2

0.0127 second after the flash. The globe has begun to contract. Every third frame is shown.

3

0.0147 second after the flash.

4

0.0165 second after the flash.

5

0.0185 second after the flash.

6

0.0203 second after the flash. To time maximum compression every frame is shown from here on.

7

0.0210 second after the flash.

8

0.0216 second after the flash. The fine streamers make the minimum diameter difficult to measure.

9

0.0223 second after the flash. This is the end of the first contraction. The internal gas pressure is estimated to be 2500 atmospheres.

10

0.0229 second after the flash. The minimum has probably now been passed. Motion at the pressure peak is very fast.

11

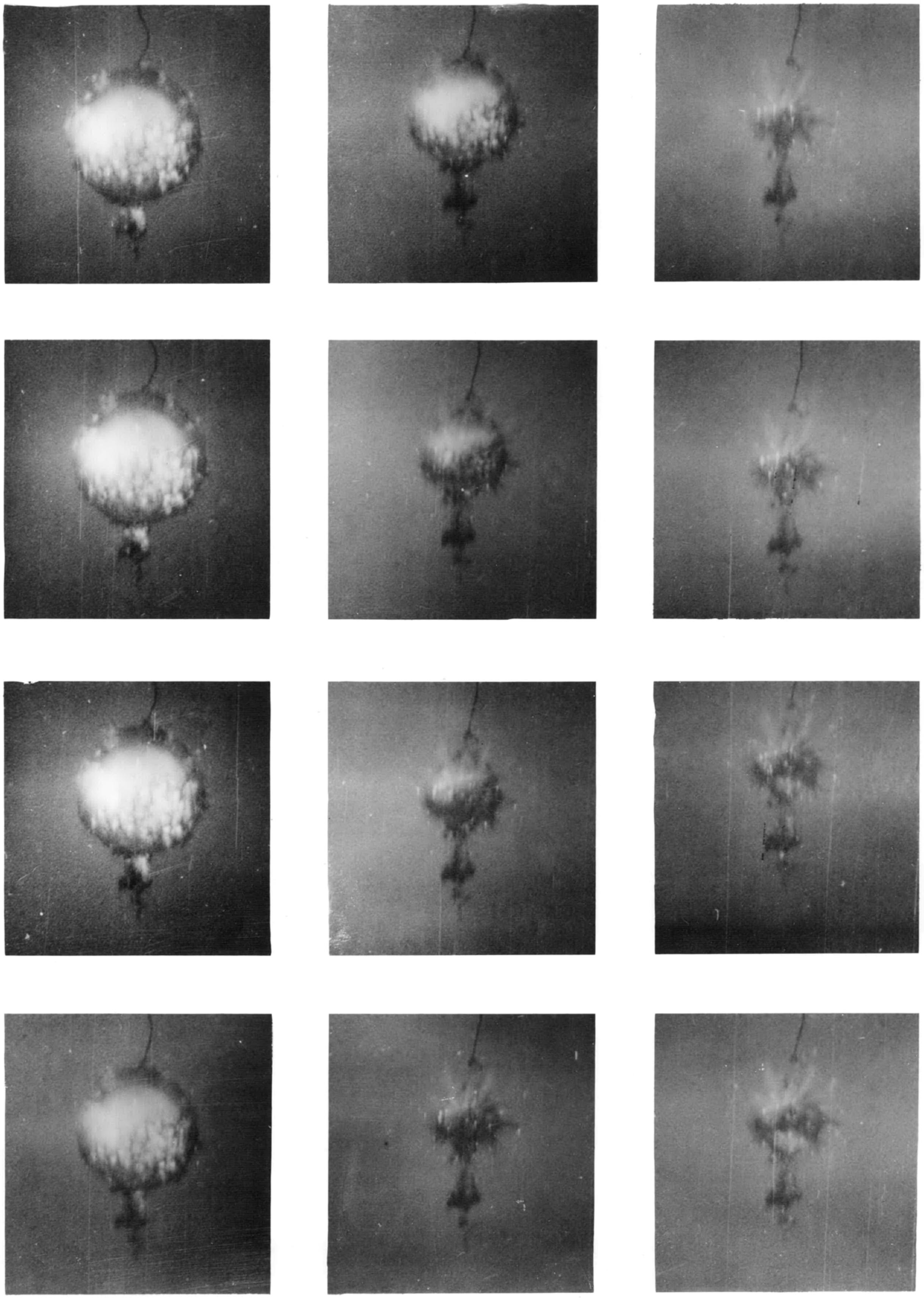
0.0235 second after the flash. The globe has begun its second expansion.

12

0.0242 second after the flash. The next four frames are omitted.

Figure 7 - High-Speed Photographs of a Pulsating Gas Globe

The charge was at a depth of 36 inches. This series is a continuation of the one in Figure 6.



1

0.0273 second after the flash. 3 frames are omitted.

2

0.0299 second after the flash. With a diameter of 7.2 inches, the globe is near its second maximum expansion. 4 frames are omitted.

3

0.0330 second after the flash. The spherical form is still well defined. 2 frames are omitted.

4

0.0345 second after the flash. Frames shown from this point are spaced irregularly.

5

0.0383 second after the flash. This is the second contraction.

6

0.0610 second after the flash.

7

0.0661 second after the flash. The globe is losing its neat spherical shape.

8

0.0764 second after the flash.

9

0.0866 second after the flash.

10

0.0969 second after the flash.

11

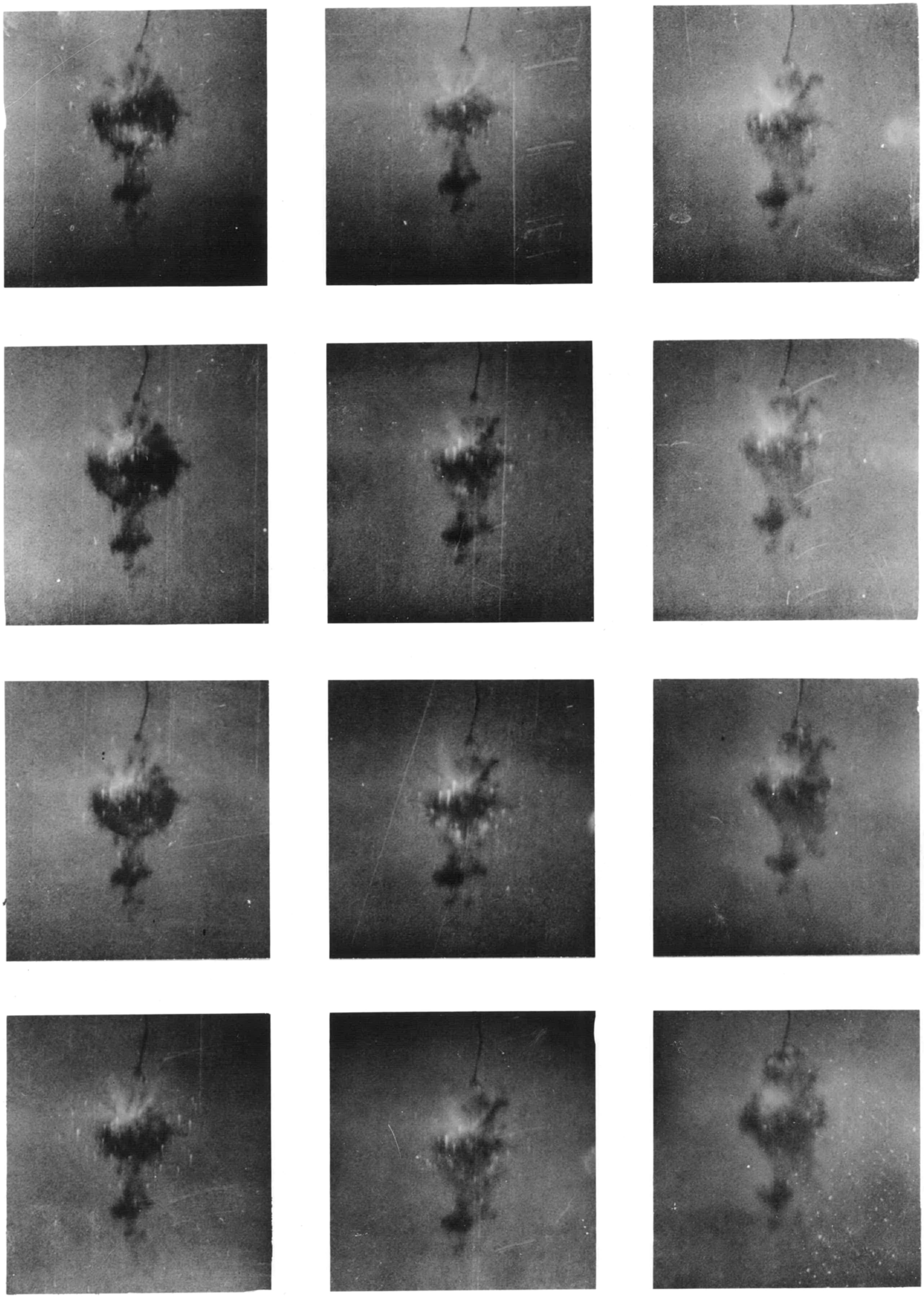
0.1322 second after the flash.

12

0.1829 second after the flash. The globe is losing its spherical form and is moving upward under the influence of buoyancy.

Figure 8 - High-Speed Photographs of a Pulsating Gas Globe

The charge was at a depth of 36 inches. This series is a continuation of the ones shown in Figures 6 and 7.



11 inches. The globe appears perfectly spherical with small protuberances on its surface and a long tail at the lower side. It is suggested that the protuberances are pieces of the charge container which are moving outward at a higher speed than the outer boundary of the gas globe. The tail on the lower side may be caused by the lower end of the charge container, which is blown out into the surrounding water. It is well to avoid hasty conclusions on the influence of form of charge, which occupies only a small part of the container.

The first expansion to 11 inches is followed by a contraction to a much smaller diameter, probably around 1 inch. During this phase of the motion the protuberances appear to lag behind the globe surface, leaving fine streamers in the water outside the globe. It should be noted that these streamers and a fine fog make it very difficult to measure accurately the minimum diameter and that the experimental curves of diameter as a function of time are therefore to be looked upon with some suspicion.

From each series of pictures like those in Figures 6, 7, and 8, a curve is plotted showing globe diameters as a function of time. Three such plots, for 36-, 24-, and 12-inch depths, in water free from wall or bottom influences, are given in Figures 9, 10, and 11. The observed values are plotted as solid lines, and the broken curves indicate the diameters that may be expected from hydrodynamic considerations. The theoretical minimum values

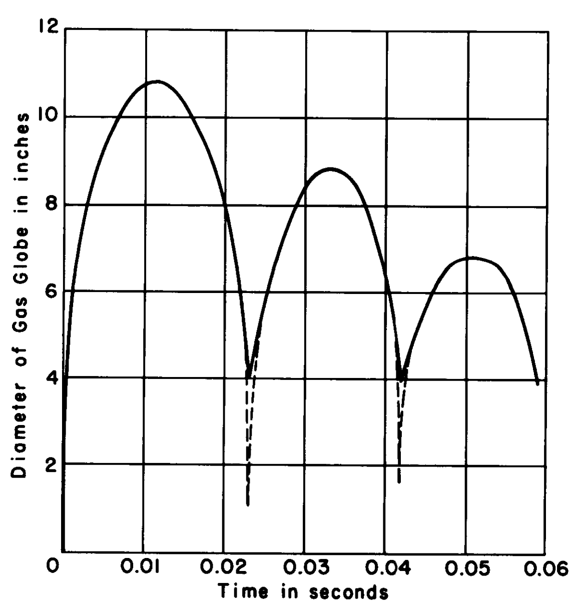


Figure 9 - Curve of Diameter on Time for a Charge 36 inches below the Water Surface

The broken lines are obtained from theoretical considerations.

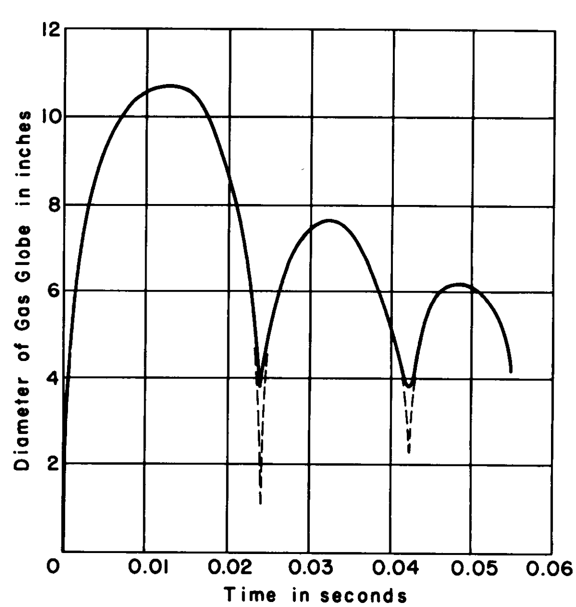


Figure 10 - Curve of Diameter on Time for a Charge 24 inches below the Water Surface

The broken lines are obtained from theoretical considerations.

are obtained from the work of Kennard and are based on the assumption that the volume changes adiabatically. The measured time for the full cycle of expansion and contraction is about 0.023 second. Subsequent expansions and contractions are evident in the motion pictures, but the variation in diameter soon becomes hard to follow exactly. There appears to be little variation in pulse frequency or diameter resulting from firing the charges at the three different depths.

A summary of the information obtained from the curves of Figures 9, 10, and 11 is contained in Table 1.

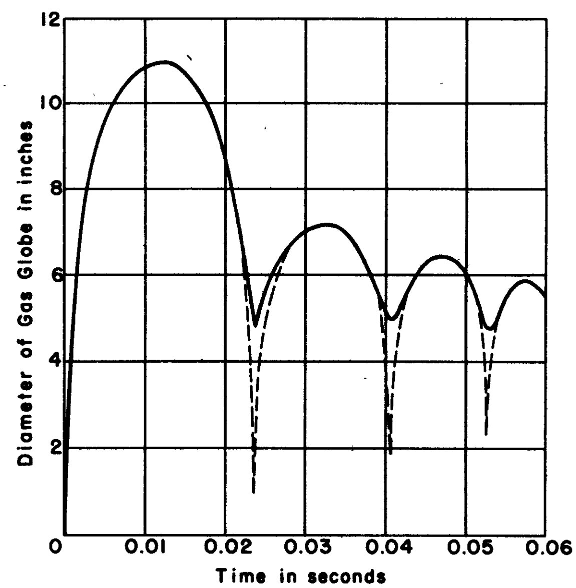


Figure 11 - Curve of Diameter on Time for a Charge 12 inches below the Water Surface

The broken lines are obtained from theoretical considerations.

The work of expansion is taken to be the product of the volume of the fully expanded globe and the pressure opposing the expansion. For comparison with other energy data it is noted that the explosive material in the detonator consists of tetryl 0.42 gram, lead azide 0.16 gram, ground pyro 0.07 gram, potassium chlorate

TABLE 1

Observed Data on Explosion of a Number 8 Detonator in Free Water at Atmospheric Pressure

Depth below Surface inches	Cycle Number	Maximum Diameter inches	Duration of Cycle seconds	Work of Expansion* inch pounds
36	1	11.0	0.023 mean 23	9950
	2	7.2	0.016 17	2740
	3	6.4	0.012 14	1770
24	1	10.8	0.024	9220
	2	7.6	0.019	3190
	3	6.4	0.013	2180
12	1	10.8	0.023	8950
	2	8.3	0.019	4470
	3	6.9	0.017	2310

* Product of maximum volume by the atmospheric pressure and the hydrostatic head.

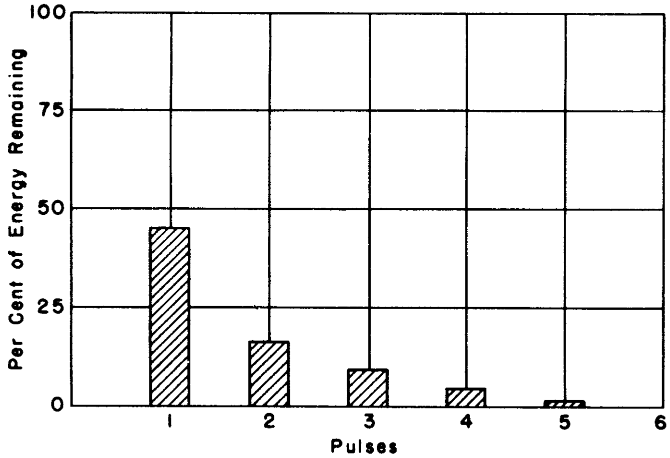


Figure 12 - Typical Energy Dissipation

The shaded areas for the pulses are taken at the point of maximum expansion.

0.03 gram, lead salt 0.03 gram, total 0.71 gram. Figure 12 shows graphically the work of expansion at successive cycles in a series. A decrement ratio of about one-half per cycle is indicated in this case; both lower and higher values are observed in other cases.

As many as 17 successive pulses have been observed on viewing some of the motion pictures, but most of them cease visibly before 7 cycles have passed. The gas globe then breaks up into small bubbles which move toward the water surface under the influence of their buoyancy.

2. Explosion near a Vertical Wall

Early theoretical and experimental studies of Bjerknes (8) suggest that the motion of a pulsating globe is appreciably altered by the proximity of the globe to a rigid surface. The experiments described in the foregoing section of this report were repeated in the vicinity of a solid wall, using the same methods as before. Data like those of Figures 9, 10, and 11 are now presented in Figure 13, a to g, for a series of explosions all at constant depth of 30 inches below the surface, but variable distance from a solid concrete vertical wall. These show that the period of pulsation and the diameter

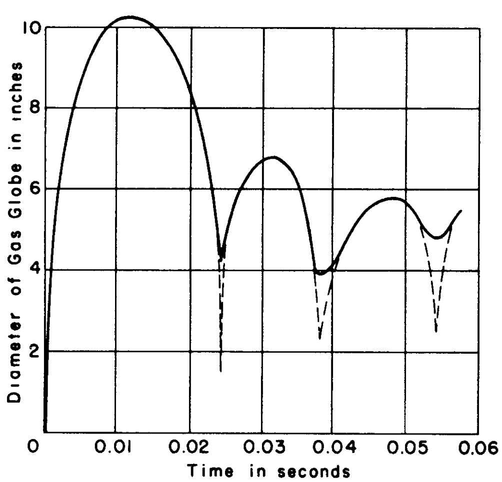


Figure 13a - Charge 24 inches from Wall

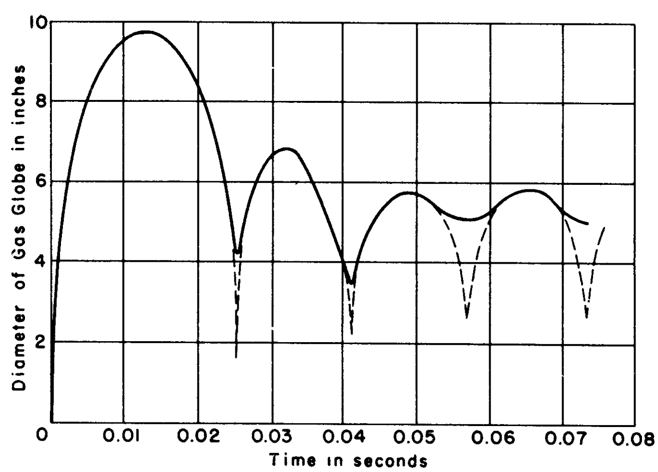


Figure 13b - Charge 18 inches from Wall

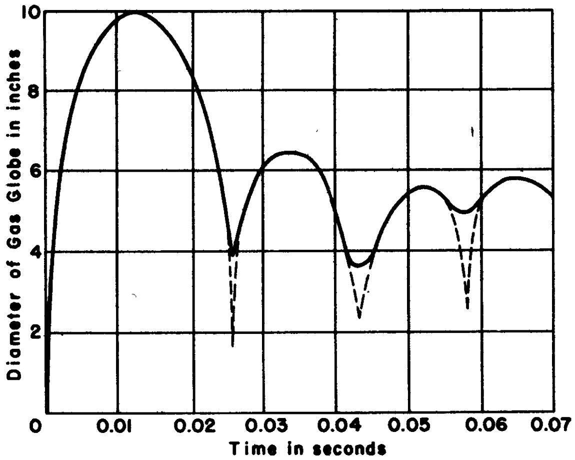


Figure 13c - Charge 12 inches from Wall

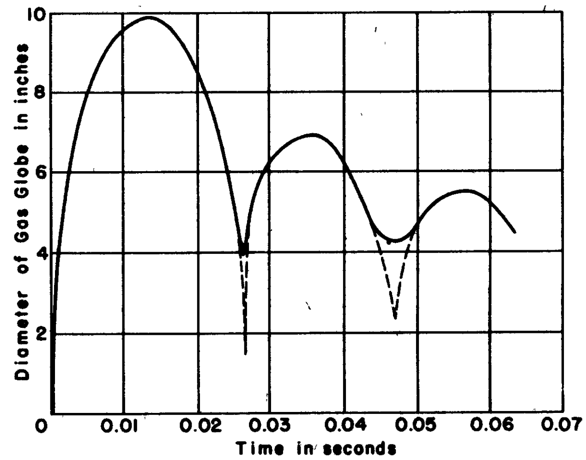


Figure 13d - Charge 9 inches from Wall

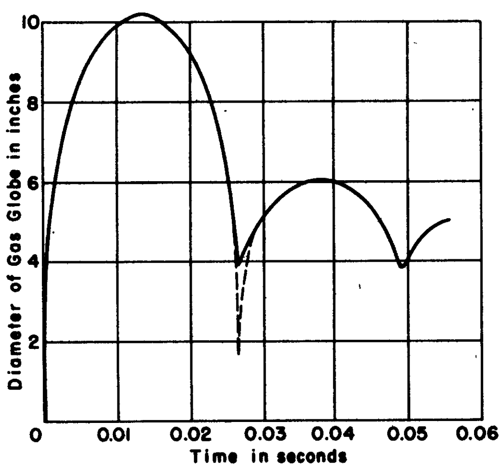


Figure 13e - Charge 6 inches from Wall

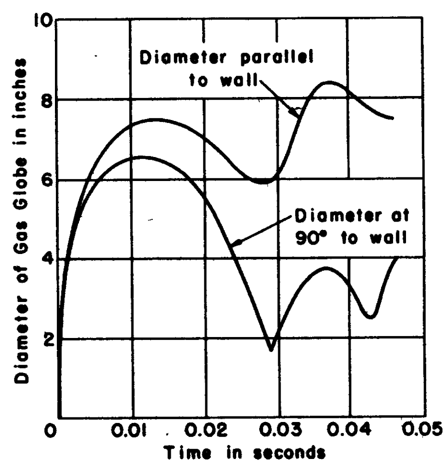


Figure 13f - Charge 3 inches from Wall

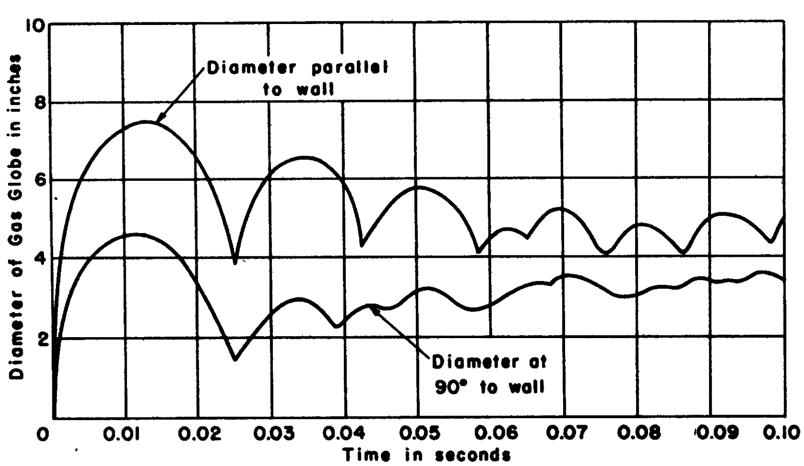


Figure 13g - Charge in Contact with Wall

Figure 13 - Curves of Diameter on Time for a Charge at Various Distances from a Vertical Wall

1
The flash again shows, as in the first frame of Figure 6, but it preceded the exposure of this film a little more, by 0.0001 second.

2
After omission of one frame the third is shown, 0.0015 second after the flash. Note the shadow of the globe in the rear (west) wall. The fourth frame is also omitted.

3
Fifth frame, 0.0028 second after the flash. The features seen in Figure 6 are accurately repeated.

4
Seventh frame, 0.0042 second after the flash. The protuberance below is long and slender.

5
0.0056 second after the flash. The protuberance has two breaks in direction.

6
0.0076 second after the flash. Extension of the protuberance has ceased.

7
0.0097 second after the flash.

8
0.0117 second after the flash. This is near the maximum of the first expansion.

9
0.0138 second after the flash.

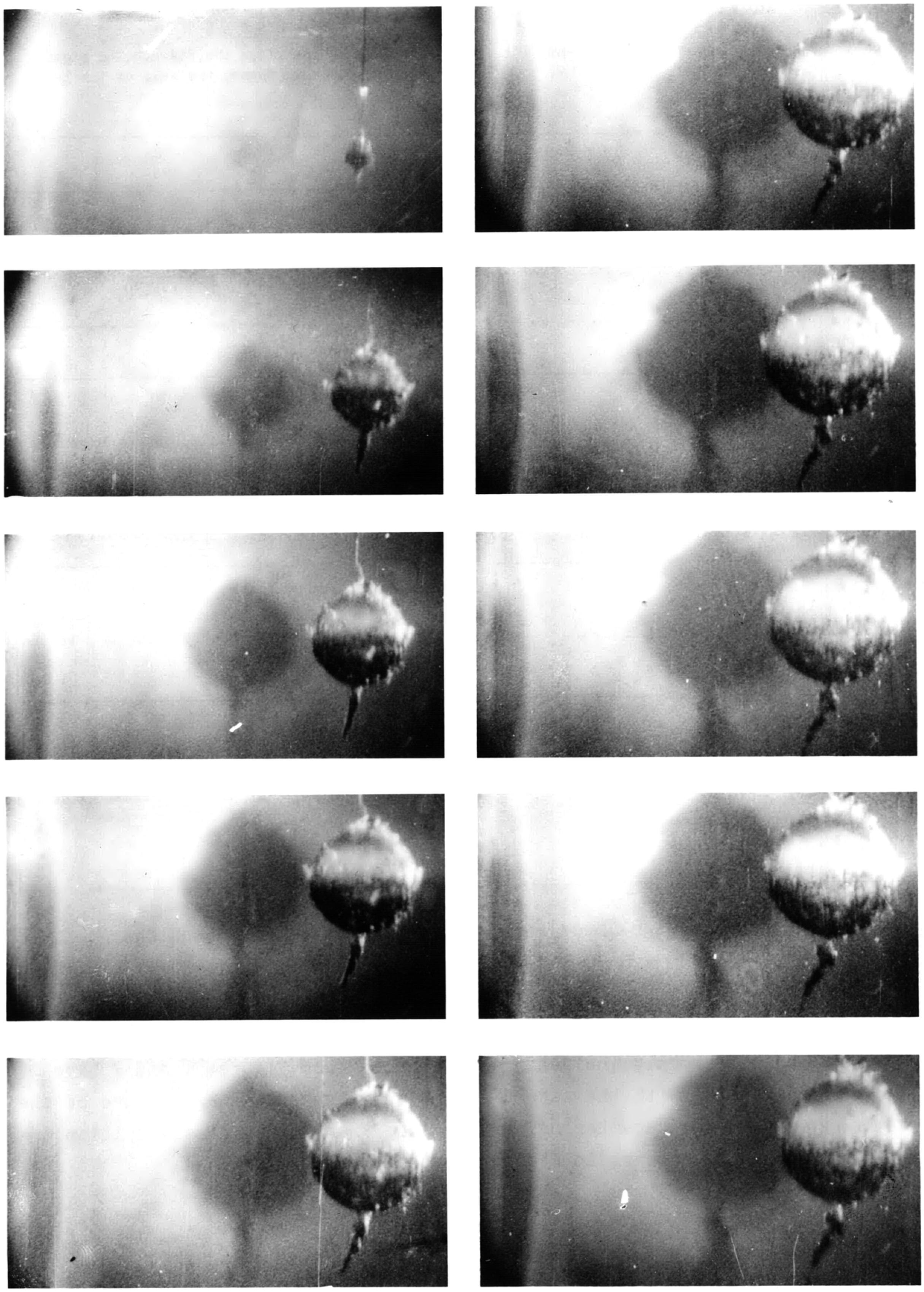
10
0.0158 second after the flash. The compression phase has definitely begun.

Figure 14 - High-Speed Photographs of a Pulsating Gas Globe

The charge was 24 inches from the wall.

of a globe near a vertical wall differ little from those in free water. However, this series presents important new information, relating especially to the migration of travel of the gas globe. A detailed series of photographs is therefore presented in Figures 14 to 19.

Representative frames from the high-speed motion pictures, Figures 14 to 19, clearly show the motion of the pulsating globe. They show that the initial phase is the same as that in free water. Following the detonation, the gas globe simply expands, forcing the surrounding water ahead of it. This is the phase of the action shown in Figure 14. The position of the globe with reference to the light and camera is shown in Figure 2 and may be followed in Figure 14 by the shadows cast on the two walls; it is necessary to bear in mind the reversal caused by the mirror, however, which causes the west wall to appear in the left in Figure 14, although it is really on the right, as shown in Figure 2.



1

0.0202 second after the flash. The globe is still centered on its original position.

2

0.0210 second after the flash. The shadow on the left (north) wall gives a clear sense of position and distance.

3

0.0220 second after the flash.

4

0.0226 second after the flash.

5

0.0233 second after the flash. This is the end of the first compression.

6

0.0240 second after the flash. The globe starts to move toward the wall at the left.

7

0.0247 second after the flash.

8

0.0254 second after the flash. The spherical form of the globe persists.

9

0.0266 second after the flash. The streamers and protuberances are nearly stationary in the water.

10

0.0286 second after the flash. The globe approaches its second maximum expansion, much smaller than the first.

Figure 15 - High-Speed Photographs of a Pulsating Gas Globe

The charge was 24 inches from the wall. This series is a continuation of the one shown in Figure 14.

In Figure 15 the compressive motion following the first expansion is shown, and so far only incidental differences from Figures 6 and 7 have appeared. Beginning with the second expansion, however, a new feature of the motion appears in the decentering of the globe from its original position toward the wall which appears in Figures 14 to 16 on the left.

1

0.0329 second after the flash. Compression begins after the second maximum expansion.

2

0.0356 second after the flash. The gas globe is contracting.

3

0.0369 second after the flash. The decentering motion continues.

4

0.0376 second after the flash.

5

0.0383 second after the flash. This is the second point of maximum compression.

6

0.0397 second after the flash. The motion of the whole globe to the left continues.

7

0.0431 second after the flash.

8

0.0506 second after the flash. At the end of the second compression the water from the right retains its velocity to the left, and here breaks through to form a new leftward protuberance.

9

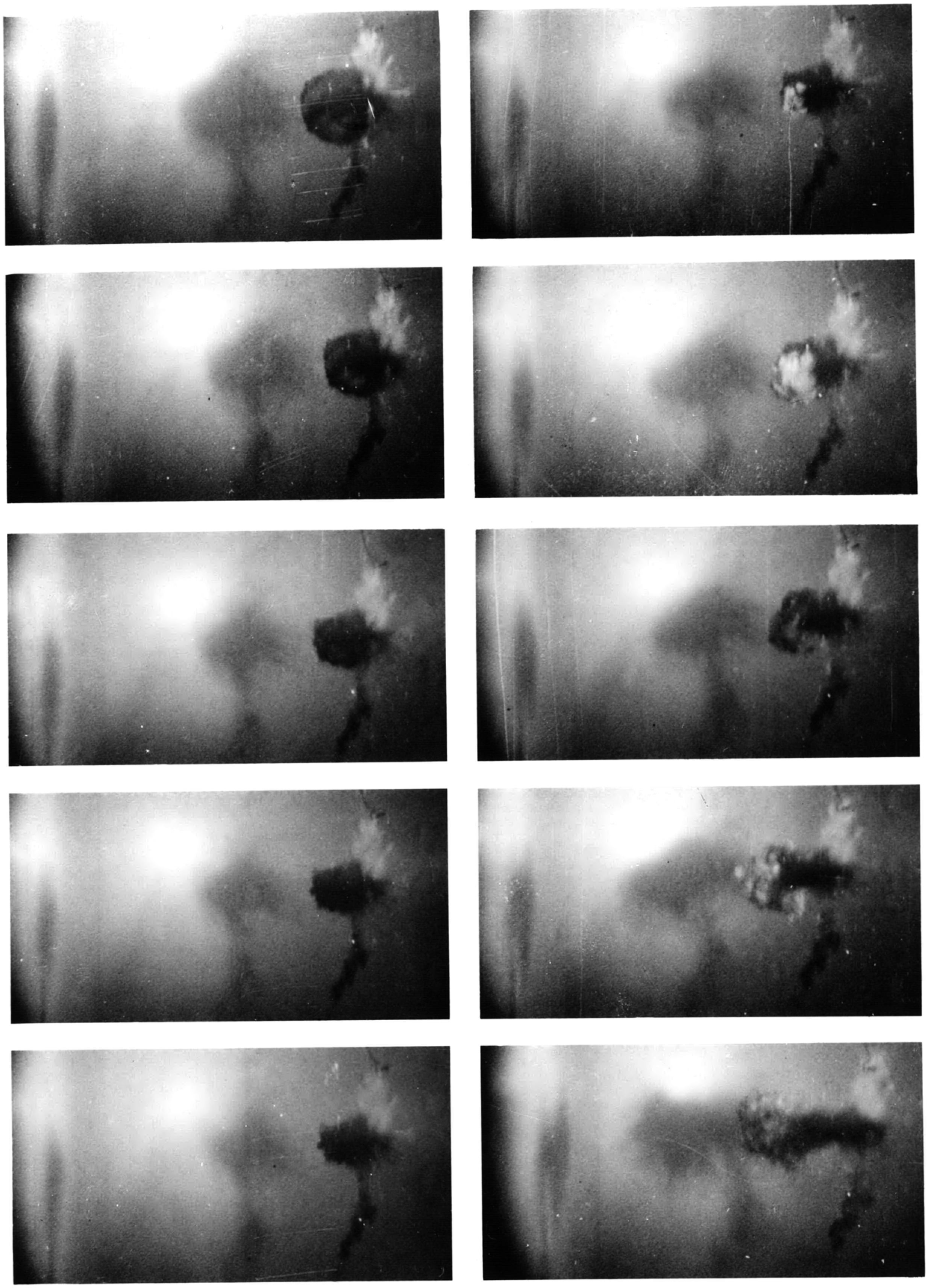
0.0752 second after the flash. The shadow on the left wall shows detachment of a second globe to the rear.

10

The gas globe still moves toward the wall and is starting to break up into small bubbles which move toward the surface.

Figure 16 - High-Speed Photographs of a Pulsating Gas Globe

The charge was 24 inches from the wall. This series is a continuation of the ones shown in Figures 14 and 15.



1

0.0232 second after the flash. The first cycle is near its end at the point of maximum compression.

2

0.0241 second after the flash. The decentering motion begins.

3

0.0250 second after the flash. The globe is expanding and moving left toward the wall.

4

0.0259 second after the flash.

5

0.0287 second after the flash. The globe is approaching the second maximum expansion.

6

0.0408 second after the flash. This is the second peak of compression. The leftward protuberance is prominent.

7

0.0417 second after the flash.

8

0.0444 second after the flash. The globe is approaching the third maximum expansion.

9

0.0472 second after the flash. The globe has nearly overtaken the leftward protuberance.

10

0.103 second after the flash. The globular form is lost as confirmed by the shadows. A new leftward protuberance forms.

11

0.124 second after the flash. The gas globe is nearing the wall.

12

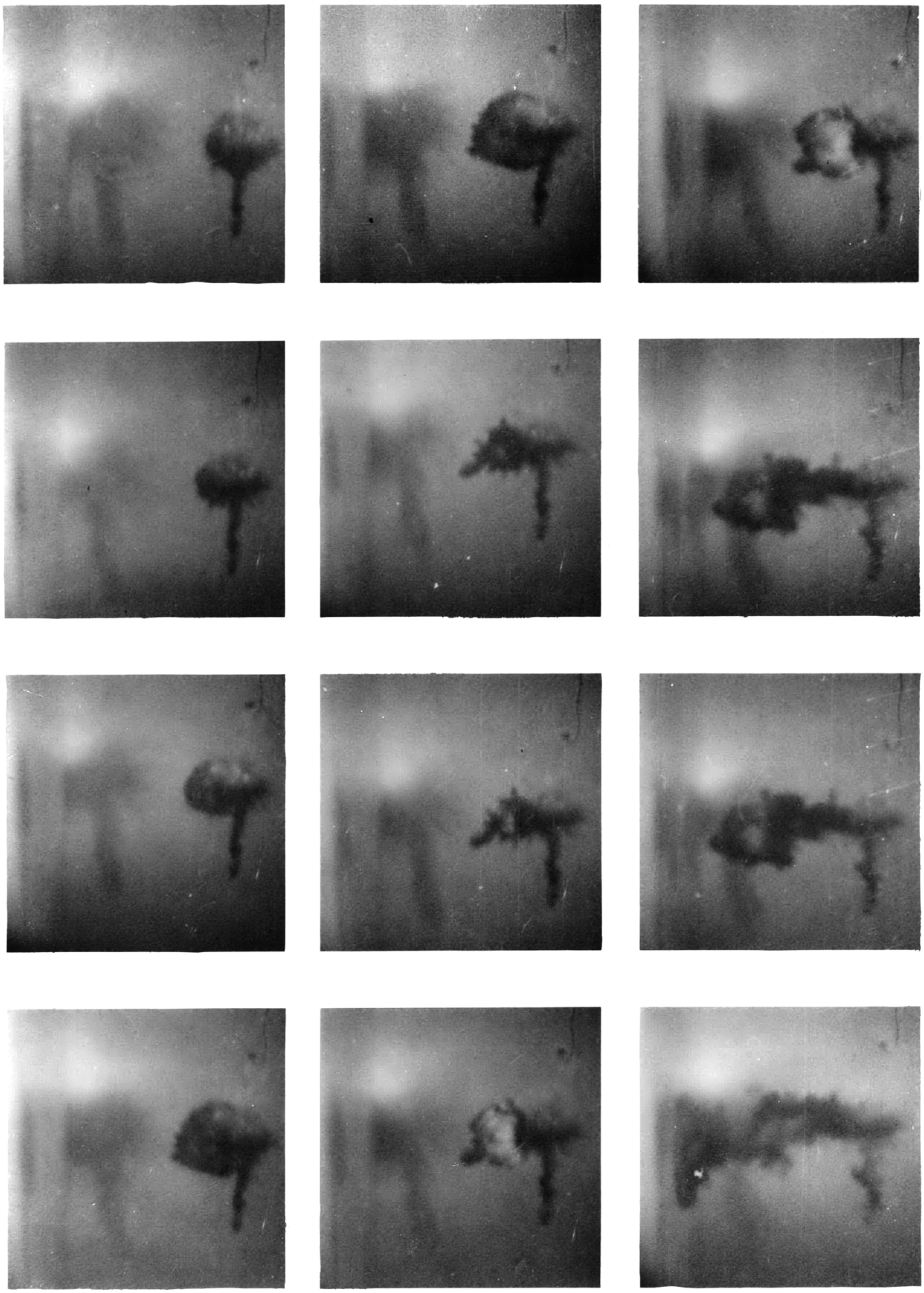
The globe expands and spreads against the wall.

Figure 17 - High-Speed Photographs of a Pulsating Gas Globe

The charge was 18 inches from the wall.

Details of this latter process are better seen in later series starting from positions nearer the wall, and shown in Figures 17, 18, and 19.

(Text continued on page 30)



1

Picture shows the cap prior to the flash, 6 inches from the wall. The wall is shown by the light area at the left and the cap is just to the right of it.

2

0.0106 second after the flash. The globe is nearing the first maximum expansion. Note that the globe is almost a perfect sphere, notwithstanding its proximity to the wall.

3

0.024 second after the flash. This is the first compression stroke. A slight decentering has already occurred.

4

0.026 second after the flash. This is the peak of compression after the first cycle.

5

0.027 second after the flash. The inrush breaks through to the left.

6

0.030 second after the flash. The globe forms a hemisphere on the wall. Note the products of combustion left behind.

7

0.031 second after the flash. The half-globe expands on the wall.

8

0.050 second after the flash. The globe collapses on the wall.

9

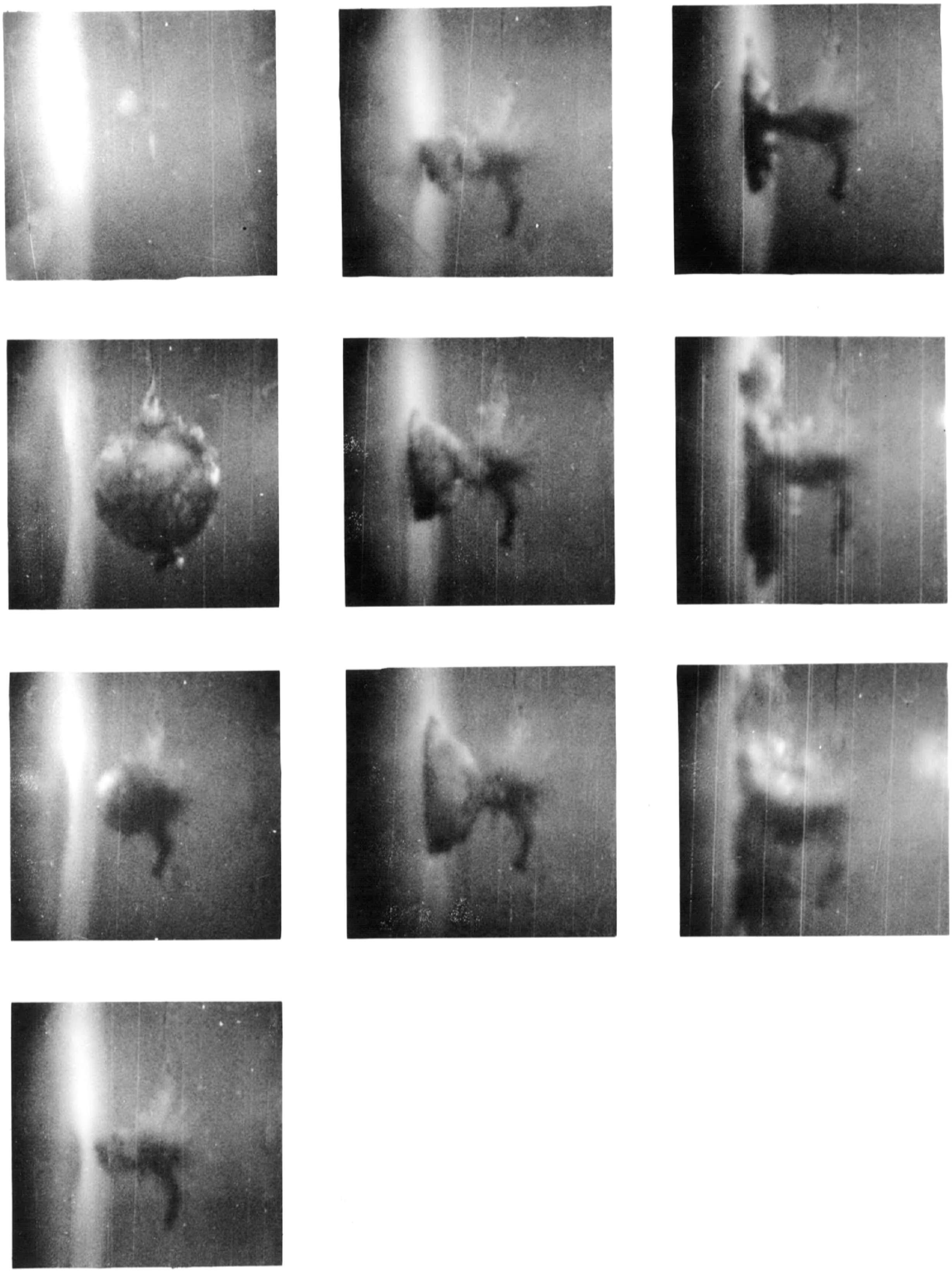
0.080 second after the flash. The globe is still pulsating.

10

The gas globe finally breaks up and heads up for the water surface.

Figure 18 - High-Speed Photographs of a Pulsating Gas Globe

The charge was 6 inches from the wall.



1

The flash of detonation coincides with the frame exposure and so marks the position of the detonator.

2

0.010 second after the flash. The gas globe at its first maximum expansion is flattened by contact with the wall, but otherwise is still rather accurately spherical.

3

0.025 second after the flash. The globe spreads out over the wall in a semi-hemispherical form.

4

0.028 second after the flash. The compression stroke is complete and the wall has received a powerful blow. After this, the globe will continue to pulsate.

1

The detonator is in contact with the wall.

2

0.003 second after the flash. A hemisphere is forming on the wall.

3

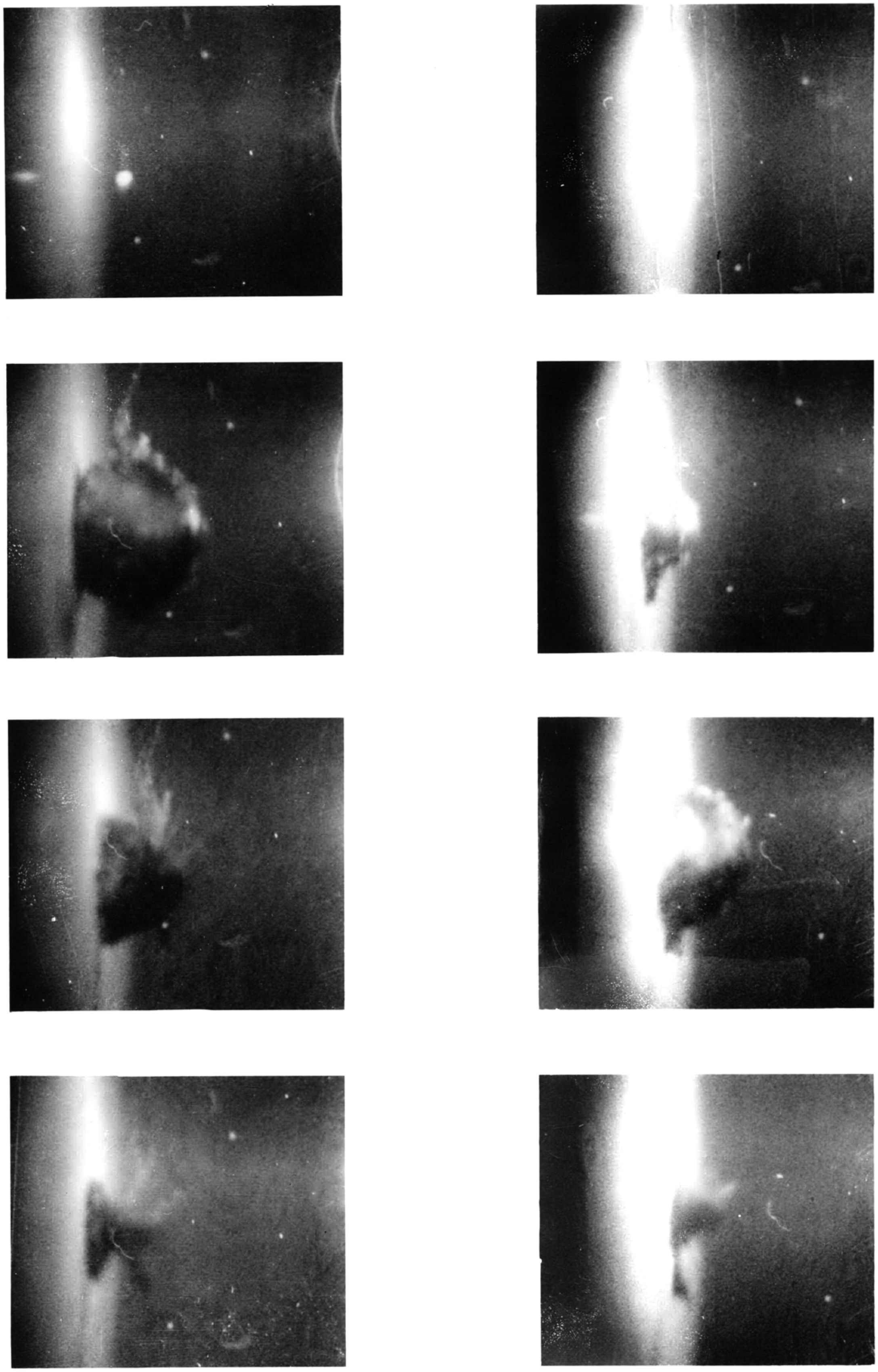
0.010 second after the flash. The hemisphere attains maximum volume.

4

0.025 second after the flash. The gas globe delivers its blow on the wall.

Figure 19 - High-Speed Photographs of a Pulsating Gas Globe

In the left-hand group the detonator was 3 inches from the wall; in the right-hand group it was in contact with the wall.



The process, at least in its early stages, may be described as a migration of the gas globe toward the wall, though in its later stages it becomes catastrophic in nature; it does not begin until the end of the first cycle. It might be said that during the first compression stroke the inward flow of the water is hindered on the wall side, but free on the opposite side, so that the net result is motion toward the wall. But no clear explanation has been found for the fact that during the outward flow during the initial expansion the presence of the wall has almost no effect until the point is reached at which the sphere actually reaches the wall. Even when this occurs the effect is mainly to cut off the part of the sphere intercepted with little change in the rest of it.

By measurement of the position of the inner and outer limbs of the sphere with respect to the wall, frame by frame, curves have been constructed to exhibit the process of migration graphically, and these are given in Figure 20, a to f. The velocity with which the globe center moves toward the wall is a maximum at the end of the first cycle and this is related to the distance from the wall at which the explosion started. A maximum velocity of approximately 200 feet per second is observed when a charge is fired at a distance of 9 inches from the wall. This falls off to smaller values when the charge is placed either at greater or at smaller

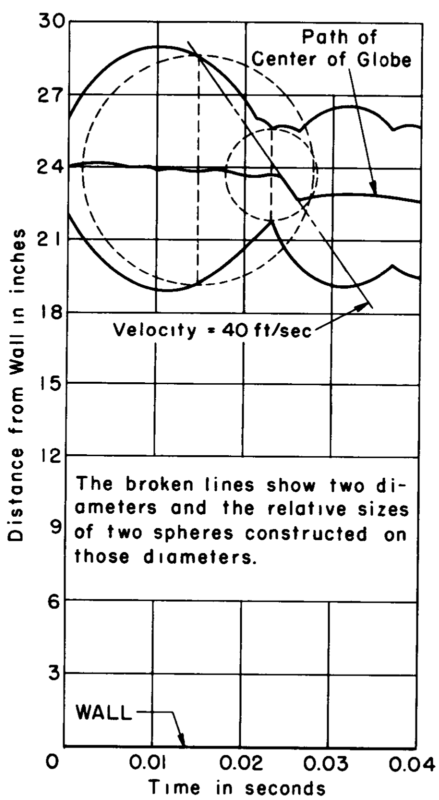


Figure 20a - Charge 24 inches from Wall

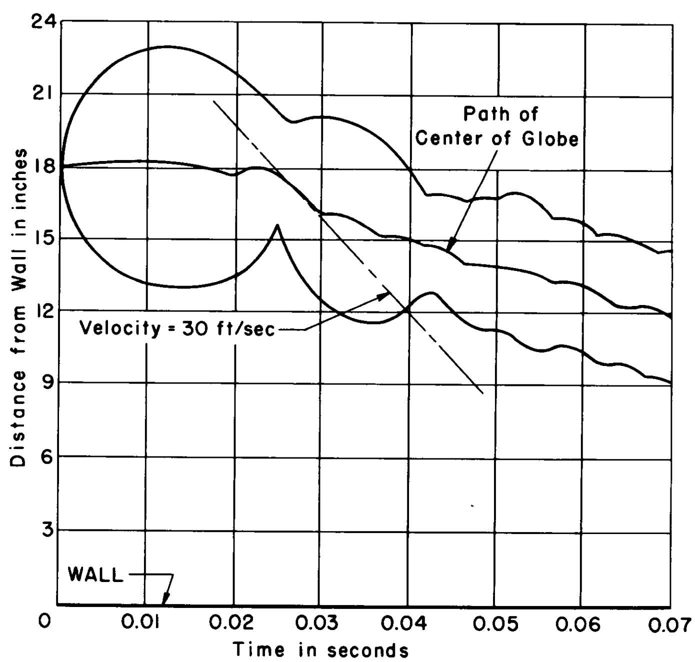


Figure 20b - Charge 18 inches from Wall

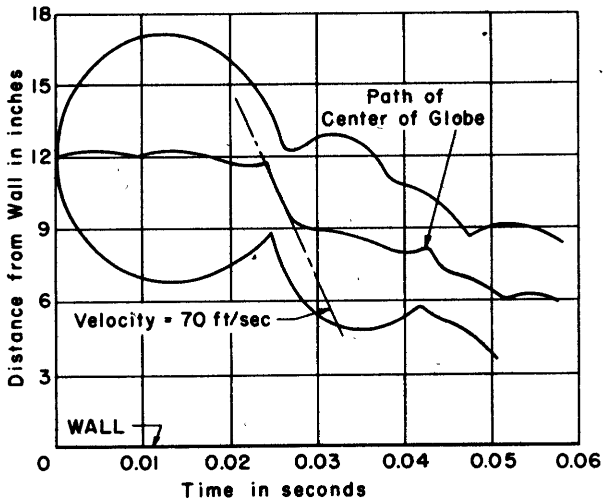


Figure 20c - Charge 12 inches from Wall

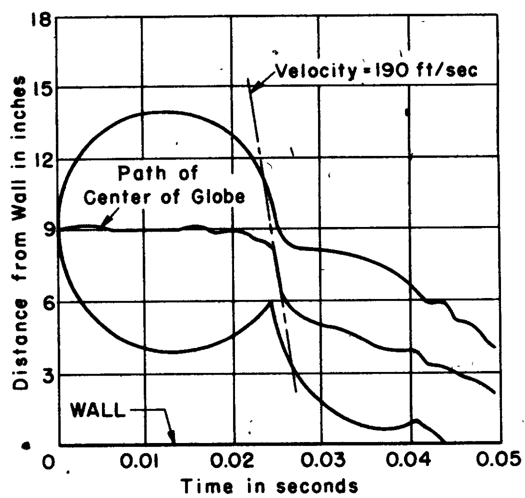


Figure 20d - Charge 9 inches from Wall

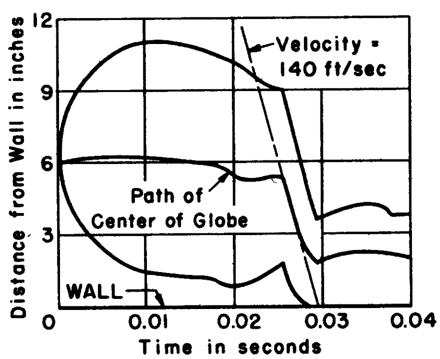


Figure 20e - Charge 6 inches from Wall

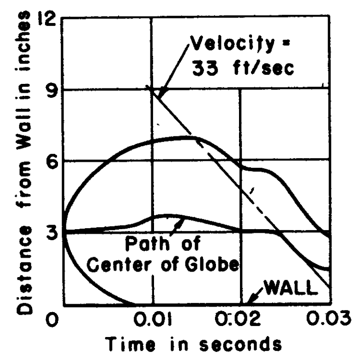


Figure 20f - Charge 3 inches from Wall

Figure 20 - Curves of Size and Position of Gas Globe formed from Number 8 Detonator in way of a Solid Vertical Wall

distances from the wall. Tangents are shown in Figure 20, a to f, and from these the curve of maximum velocity as a function of wall distance given in Figure 21 was made up.

The information gathered from this series of tests near a vertical wall is summarized in Table 2.

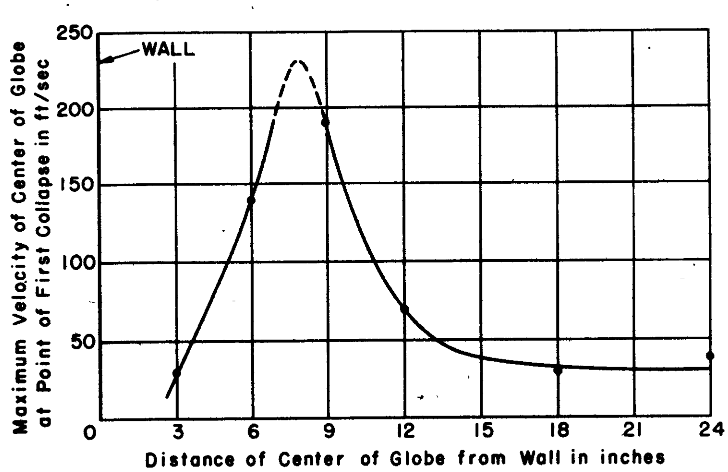


Figure 21 - Velocity of a Gas Globe toward a Rigid Surface

TABLE 2

Observed Data on Explosion of a Number 8 Detonator at 30-inch Depth and near a Vertical Wall

Distance from Wall inches	Cycle Number	Maximum Diameter inches	Duration of Cycle seconds	Work of Expansion* inch pounds
24	1	10.4	0.025	9200
	2	6.9	0.015	2700
	3	5.9	0.017	1800
18	1	9.8	0.026	7700
	2	6.9	0.016	2700
	3	5.9	0.016	1800
12	1	10.0	0.026	8200
	2	6.5	0.018	2200
	3	5.8	0.015	1700
9	1	10.0	0.027	8200
	2	7.0	0.022	2800
	3	6.5	0.017	2100
6	1	10.2	0.027	8600
	2	7.2	0.023	3000
3	1	7.7** 6.6†	0.029	3000
	2	8.5** 3.8†	0.026	
0	1	7.6** 4.6†	0.025	2000
	2	6.6** 2.7†	0.016	

* Product of maximum volume by the atmospheric pressure and the hydrostatic head.

** Diameter measured parallel to wall.

† Diameter measured at 90 degrees to wall.

3. Explosion under a Raft or Boat

The gas globe produced by the shots fired under the boat were similar in diameter and pulse frequency to the globes examined in the preceding sections. Frames taken from the high-speed motion pictures of the explosions at 6 and 0 inches under the boat are given in Figures 22 and 23.

1

The cap, supported from below, is placed 6 inches under the boat. The latter is just visible at the top of the picture.

2

0.013 second after the flash. The gas globe is at its first maximum expansion. The end-protuberance, directed upward, has already hit the boat.

3

0.0203 second after the flash. While contracting the globe starts to move toward the boat, and the protuberance widens.

4

0.0210 second after the flash. The same processes continue. A black girdle appears to separate two parts of the globe.

5

0.0217 second after the flash.

6

0.0224 second after the flash. The division into upper and lower parts is complete.

7

0.0232 second after the flash. The compression reaches its peak.

8

0.0246 second after the flash. The globe begins to form a hemisphere on the bottom of the boat.

9

0.0254 second after the flash. The hemisphere is expanding.

10

0.0290 second after the flash. The hemisphere is at its maximum volume, the lower part is small.

11

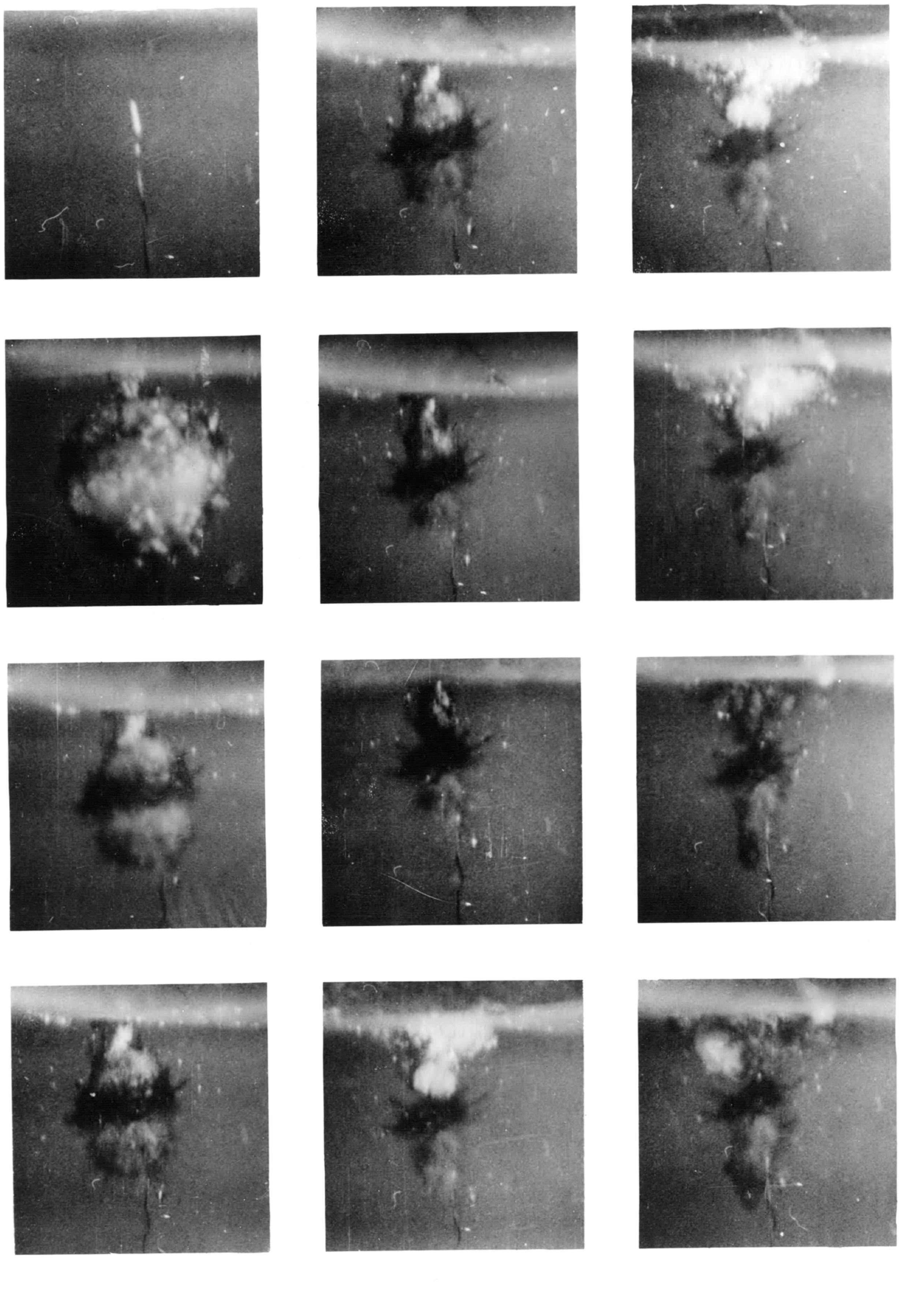
0.0362 second after the flash. The hemisphere is still pulsing.

12

0.048 second after the flash. The hemisphere again expands. The lower part moves downward.

Figure 22 - High-Speed Photographs of a Pulsating Gas Globe under the Flat Bottom of a Boat

The charge was placed 6 inches under the boat.



1

The Number 8 cap is the black object supported by a slender rod and lying horizontally in contact with the bottom of the boat. The flash in this case is below the cap.

2

0.001 second after the flash. The gas globe is forming and a wave runs out along the bottom of the boat.

3

0.01 second after the flash. The hemispheric gas globe reaches its maximum volume. The rod is bent outward.

4

0.020 second after the flash. The globe is approaching maximum compression. The rod follows the inward motion only in part.

5

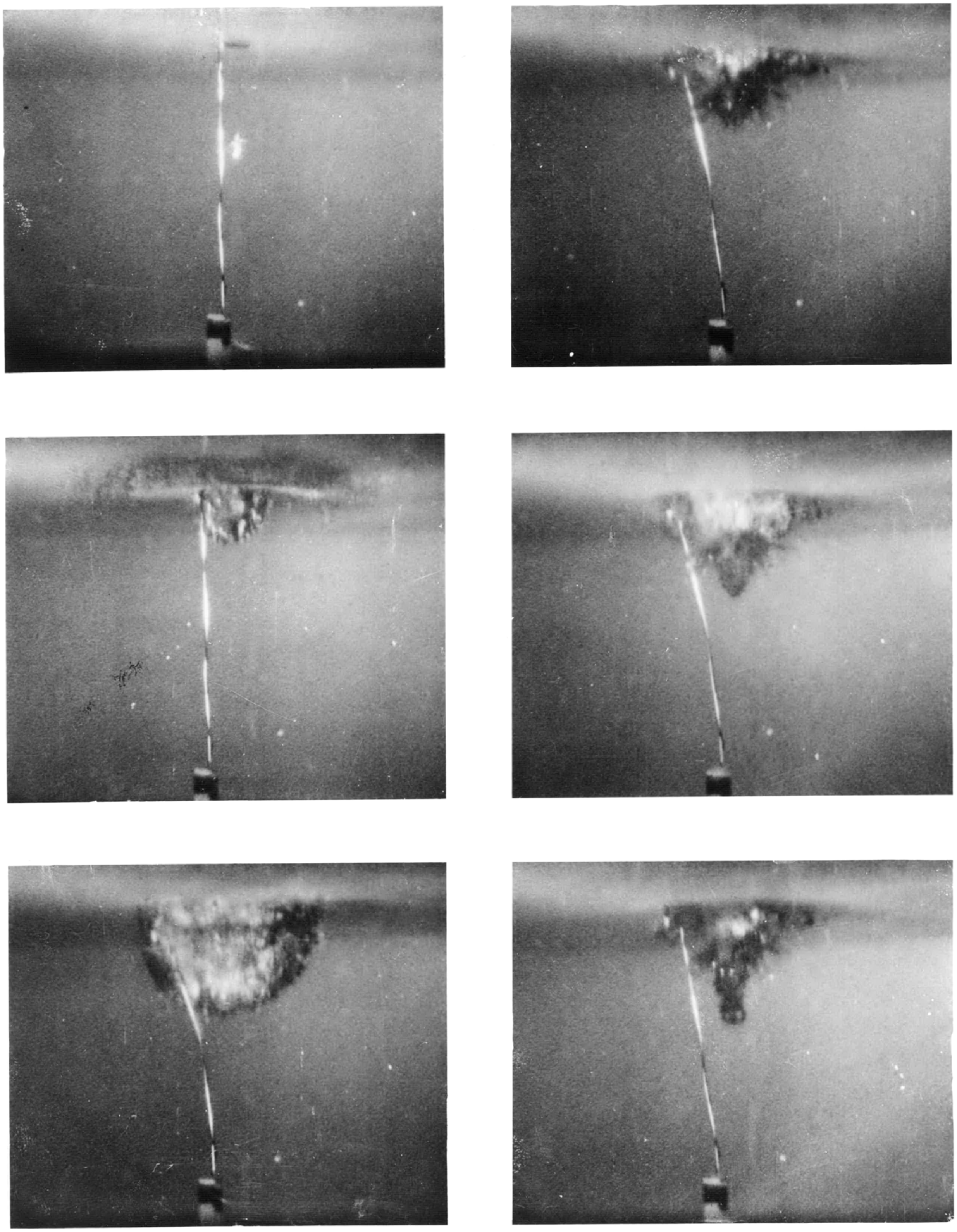
0.027 second after the flash. The gas globe starts to expand on its second cycle. The rod remains as in Number 4.

6

0.035 second after the flash. The globe is still pulsating, and a downward protuberance has formed.

Figure 23 - High-Speed Photographs of a Pulsating Gas Globe under the Flat Bottom of a Boat

The charge was placed in contact with the bottom of the boat.



Curves of diameter as a function of time are shown in Figure 24, a to e, and of position relative to the bottom of the boat in Figure 25, a and b.

The gas globe moved downward, away from the boat and away from the water surface, when the shots were fired at depths of 13 inches or more below the surface, 12 inches or more below the bottom of the boat. When a charge exploded in free water 12 inches below the surface, it moved slowly downward; however, at a depth of 7 inches, 6 inches below the boat, there was a distinct upward motion of the globe into contact with the boat bottom; see Figure 25, a and b. This motion was similar to that observed at the same distance from a vertical wall. Somewhere between depths of 7 and 13 inches

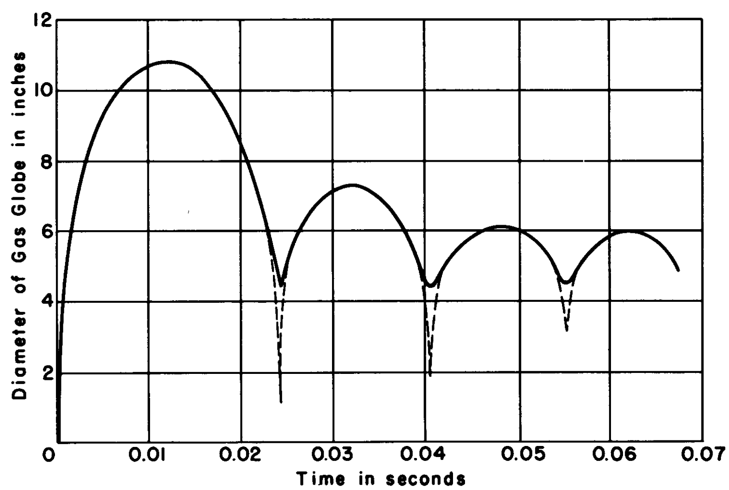


Figure 24a - Charge 24 inches under Boat

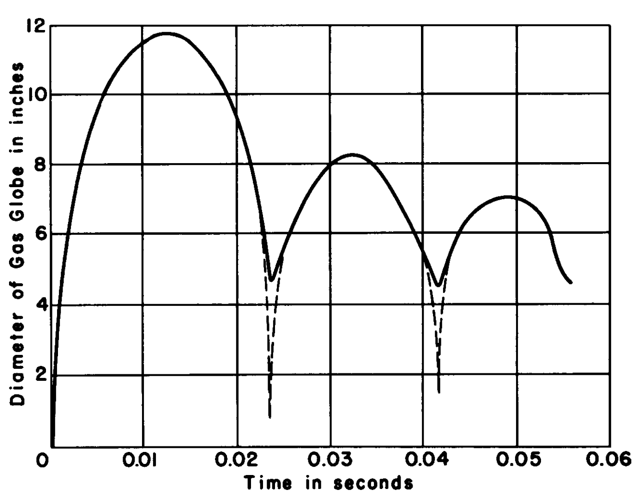


Figure 24b - Charge 18 inches under Boat

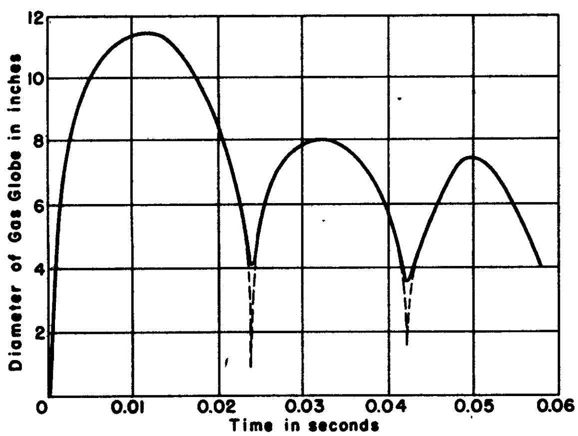


Figure 24c - Charge 12 inches under Boat

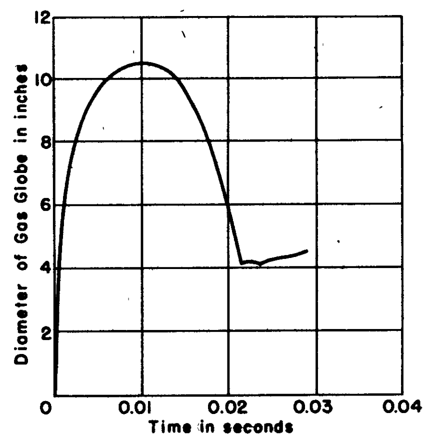


Figure 24d - Charge 6 inches under Boat

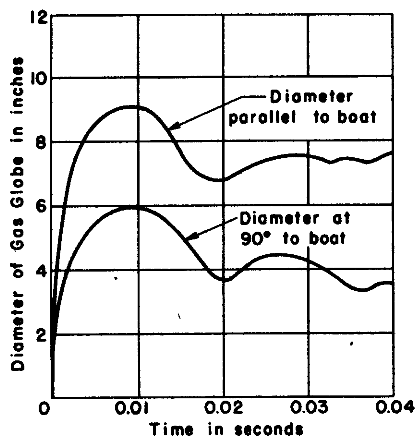


Figure 24e - Charge in Contact with Boat

Figure 24 - Curves of Size and Position of the Gas Globe formed from a Number 8 Detonator at various Depths under a Flat-Bottomed Boat

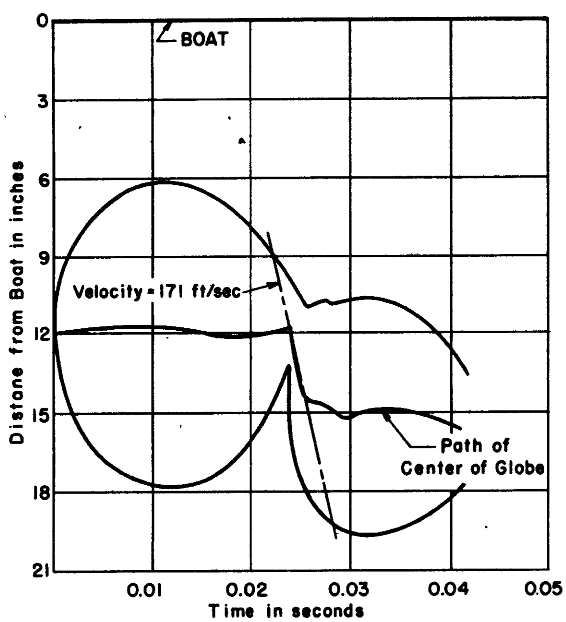


Figure 25a - Charge 12 inches under Boat

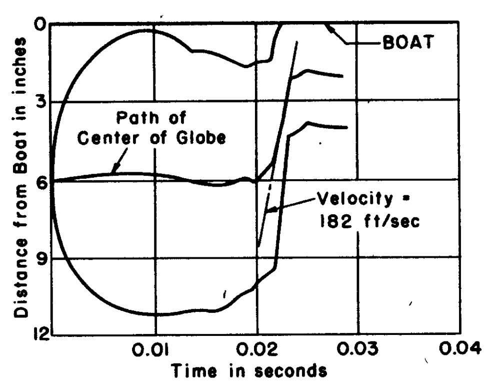


Figure 25b - Charge 6 inches under Boat

Figure 25 - Globe Diameter and Position Relative to Bottom of Boat

there is a critical point where the boat starts to exert its influence on the motion of the gas globe. This critical point will bear further investigation. All pertinent data for this group of shots are assembled in Table 3.

TABLE 3

Observed Data on Explosion of a Number 8 Detonator under a Flat-Bottomed Boat

Depth below boat* inches	Cycle Number	Maximum Diameter inches	Duration of Cycle seconds	Work of Expansion** inch pounds
24	1	10.8	0.024	9900
	2	7.3	0.017	3100
	3	6.1	0.015	1700
18	1	11.7	0.024	12400
	2	8.2	0.017	4300
	3	7.0	0.014	2700
12	1	11.4	0.024	11300
	2	8.1	0.018	4100
	3	7.4	0.015	3100
6	1	10.4	0.021	8600
0	1	9.1† 6.0††	0.020	4000
	2	7.7† 4.4††	0.013	2000

* Add 1 inch to this value to obtain depth below water surface.

** Product of maximum volume by the atmospheric pressure and the hydrostatic head.

† Diameter measured parallel to wall.

†† Diameter measured at 90 degrees to wall.

1

The charge is shown lying on the steel plate on top of the concrete block; see Figure 4 on page 5.

3

0.027 second after the flash. This is the end of the first cycle. The ignition wires remain at one side.

2

0.014 second after the flash. The vertical radius of the hemisphere is 5.2 inches, the horizontal radius 6 inches. The ignition wires are pushed aside.

4

0.035 second after the flash. This is the second expansion of the gas globe.

Figure 26 - High-Speed Photographs of a Gas Globe from a Charge in Contact with a Rigid Bottom

4. Explosions over a Hard Bottom

In contact with the top of the concrete block which served as the bottom in this series of tests, the gas globe behaved in a manner similar to that observed in contact with the wall and the bottom of the boat. The globe expanded as a hemisphere to a maximum radius of 5.2 inches in 0.014 second. The period of the first pulse was 0.027 second. For frames from the motion picture, see Figure 26.

1 — The Number 8 detonator is shown here prior to firing, lying horizontally at the end of the firing wires.

2 — 0.013 second after the flash. This is the first maximum expansion.

3 — 0.0236 second after the flash. This is the first contraction. The wires and remnants of the cap do not follow the inward flow.

4 — 0.0246 second after the flash. The gas globe starts to move toward the bottom. The protuberance is horizontal.

5 — 0.0254 second after the flash.

6 — 0.0282 second after the flash.

7 — 0.0308 second after the flash. This is the second maximum expansion.

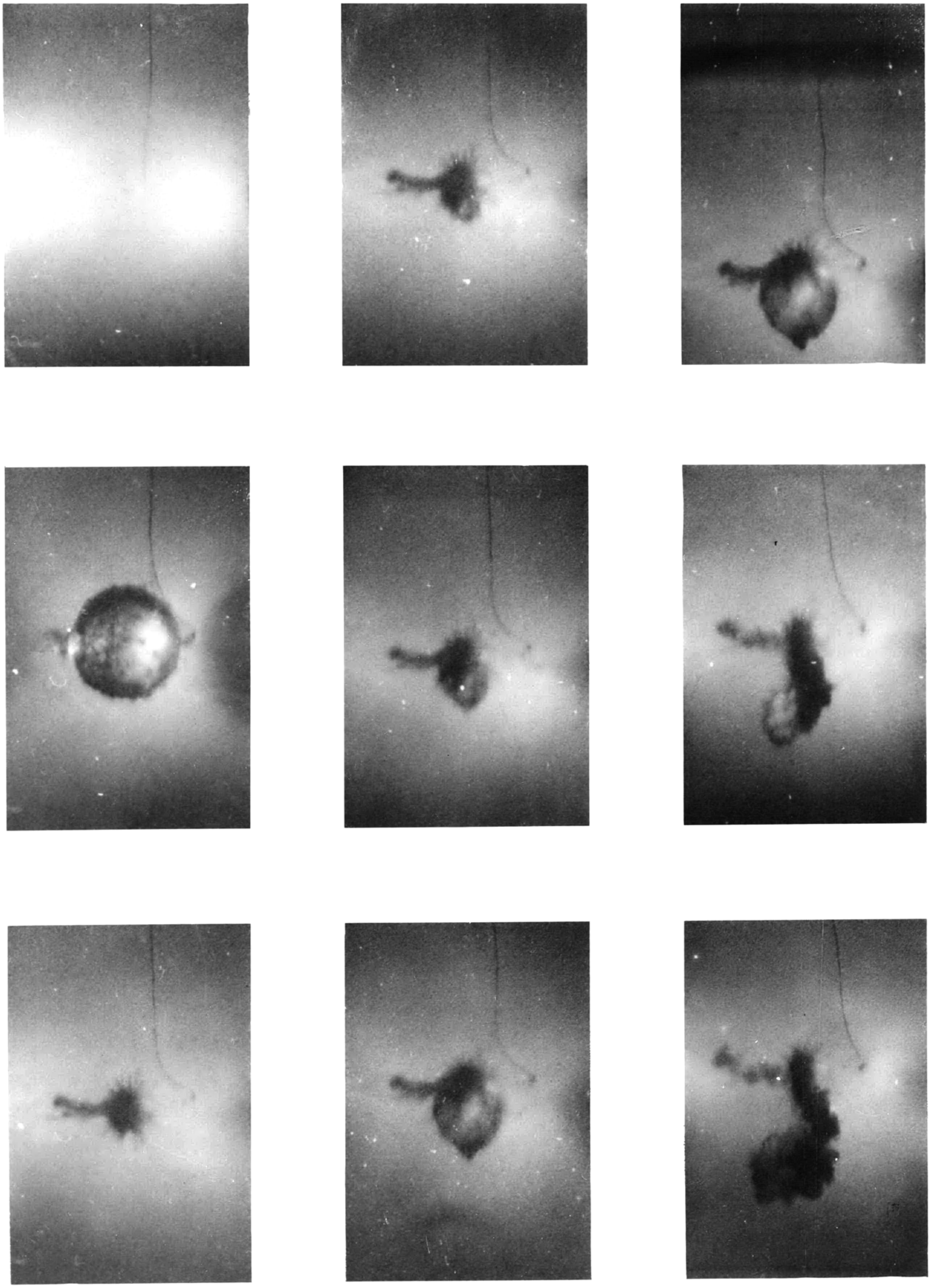
8 — 0.090 second after the flash. The motion downward is now quite pronounced.

9 — 0.204 second after the flash.

Figure 27 - High-Speed Photographs of a Gas Globe from a Charge between the Free Surface and a Rigid Bottom

The charge was 18 inches below the surface of the water and 18 inches above the top of the concrete block; see Figure 4 on page 5.

The gas globe formed by a charge at 18 inches below the surface and 18 inches above the tank bottom moved toward the bottom at the completion of the first pulse as shown in Figure 27. The initial movement carried the globe 3 inches downward at a velocity of about 63 feet per second. This was followed during succeeding pulsations by a movement of 10 inches toward the bottom at a velocity of 12 feet per second. Five inches above the bottom the globe broke up and the gas bubbles started rising toward the surface under the influence of buoyancy.



1

The detonator can be seen near the top of the photograph, lying horizontally.

2

0.011 second after the flash. This is the first maximum expansion. The sphere is complete except for the part cut off by the free surface of the water. No protuberance is formed.

3

0.017 second after the flash. The gas globe minus the lost segment is contracting and moving downward.

4

0.020 second after the flash. The downward motion continues violently.

5

0.029 second after the flash. The globe is projected downward and loses its spherical form.

6

0.045 second after the flash. This is the peak compression at the end of the second cycle.

7

0.056 second after the flash.

8

0.125 second after the flash. The broken globe moves downward.

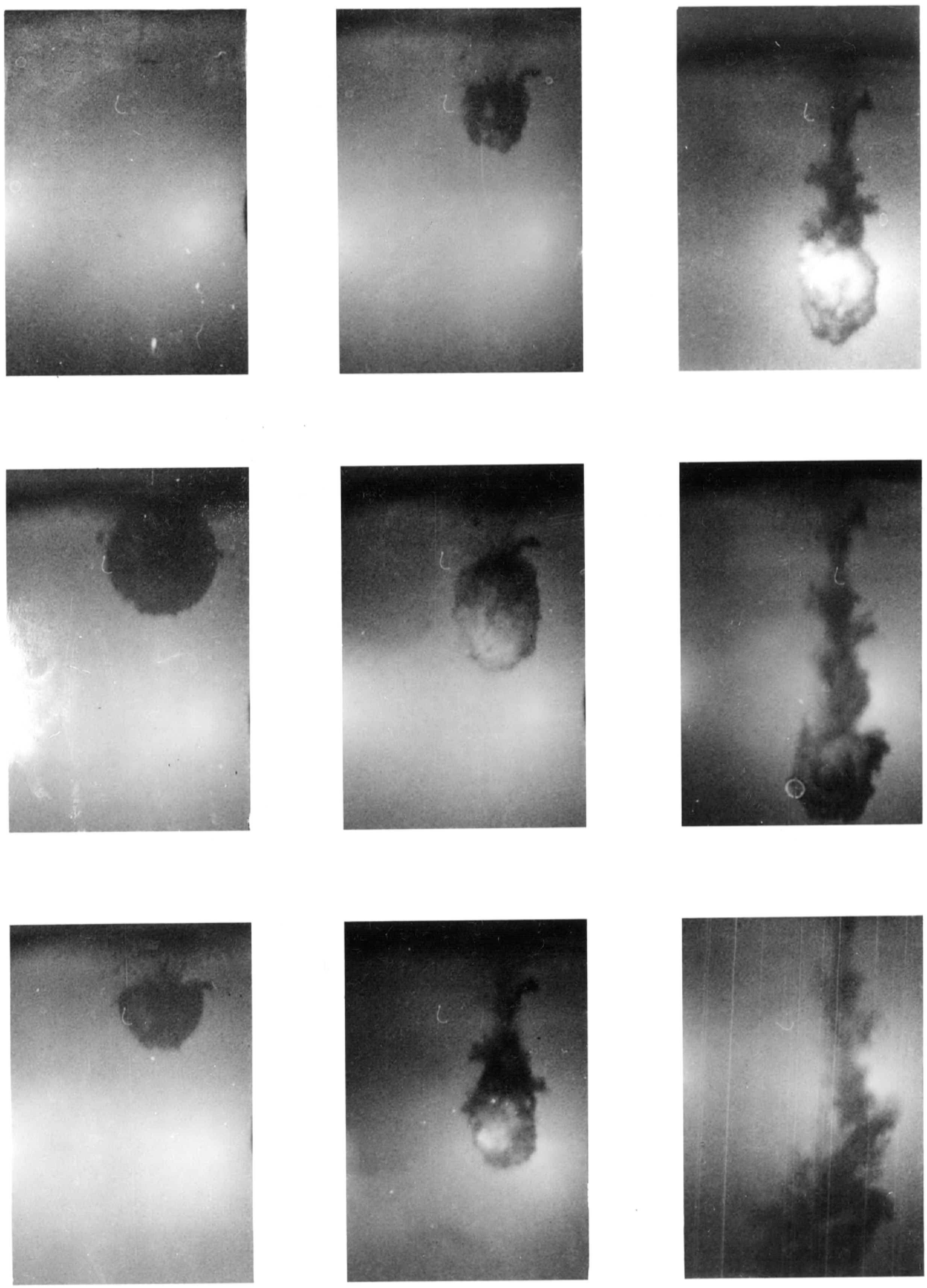
9

0.235 second after the flash.

Figure 28 - High-Speed Photographs of a Gas Globe from a Charge between the Surface and a Rigid Bottom

The charge was 3 inches below the free surface of the water and 33 inches above the top of the concrete block; see Figure 4 on page 5.

The gas globe from the charge fired 3 inches under the water surface broke through the free surface as shown in the frames taken from the motion pictures, Figure 28. Some of the gas vented into the air but a simultaneous picture of above-water events was not obtained. The bubble descended 33 inches to the bottom at an average velocity of 31 feet per second. It appeared much more turbulent than those previously examined. The first contraction which took place 0.020 second after detonation appears to be slightly faster than for most shots previously observed.



1

The detonator here is lying horizontally 1 inch under the water surface prior to firing.

2

0.013 second after the flash. Part of the gas may have vented through the water surface. Note the peculiar shape of the mirror image.

3

0.026 second after the flash.

4

0.031 second after the flash. The lower part of the globe is projected violently downward.

5

0.051 second after the flash.

6

0.140 second after the flash. A part of the gas remains near the surface.

7

0.190 second after the flash. On this expansion, more gas appears to be venting through the surface.

8

0.280 second after the flash.

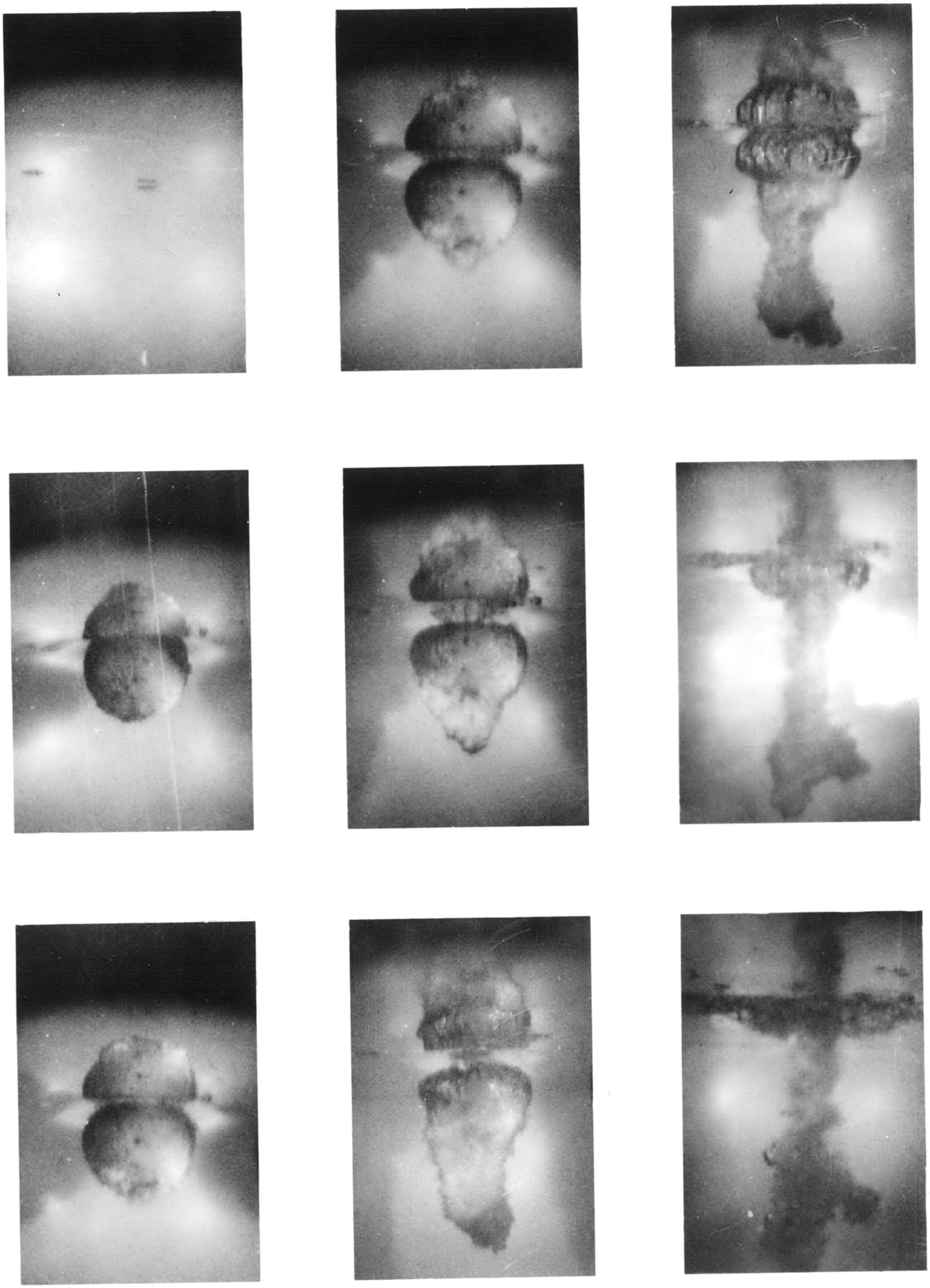
9

0.405 second after the flash.

Figure 29 - High-Speed Photographs of a Gas Globe from a Charge fired just under the Free Water Surface

The charge was 1 inch under the surface of the water and 35 inches above the top of the concrete block; see Figure 4 on page 5.

When the charge was fired 1 inch below the water surface the gas globe definitely broke through the surface, as shown in Figure 29. Small pieces of brass from the detonator case were found imbedded in the ceiling 5 feet above the basin. Personnel working on this test noted that the noise from the explosion was much greater than that produced by the other explosions of the same type of cap. The gas globe grew to a maximum diameter somewhat over 11 inches in roughly 0.026 second. This is nearly twice the time required by any of the other explosions. There was no real pulsation of the globe. After reaching the maximum diameter a lower segment of the globe slowly moved downward toward the bottom; the upper segment passed out through the water surface. The lower segment appeared very turbulent. Probably it contained a very small portion of the gas produced in the explosion, because only very small bubbles were seen to rise to the surface at the completion of the downward movement.



Data showing motion and size of the globe taken from Figures 27 and 28 have been plotted in Figure 30, a and b. The globe seen in Figure 29 from a charge 1 inch below the surface did not yield data suitable for such treatment.

In addition to the foregoing series another series of three shots were fired 10 1/2 inches above the tank bottom and 23 inches below the water surface. A number 8 cap, a mine detonator, and a charge of 1/2 ounce of tetryl were used and the photographs are shown in Figure 31, a, b, and c.

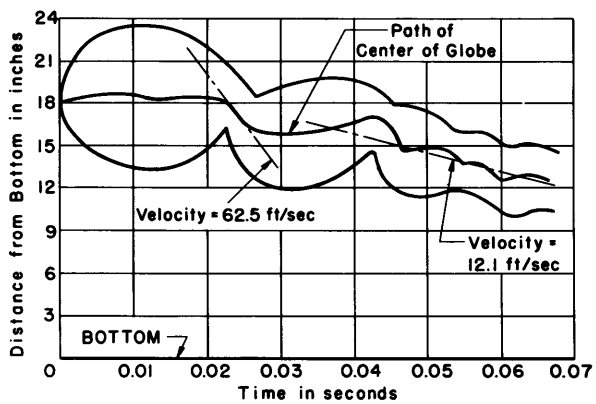


Figure 30a - Charge 18 inches under surface

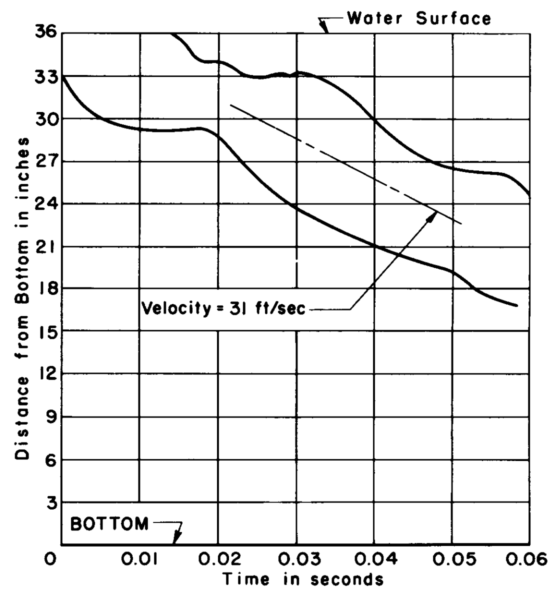


Figure 30b - Charge 3 inches under surface

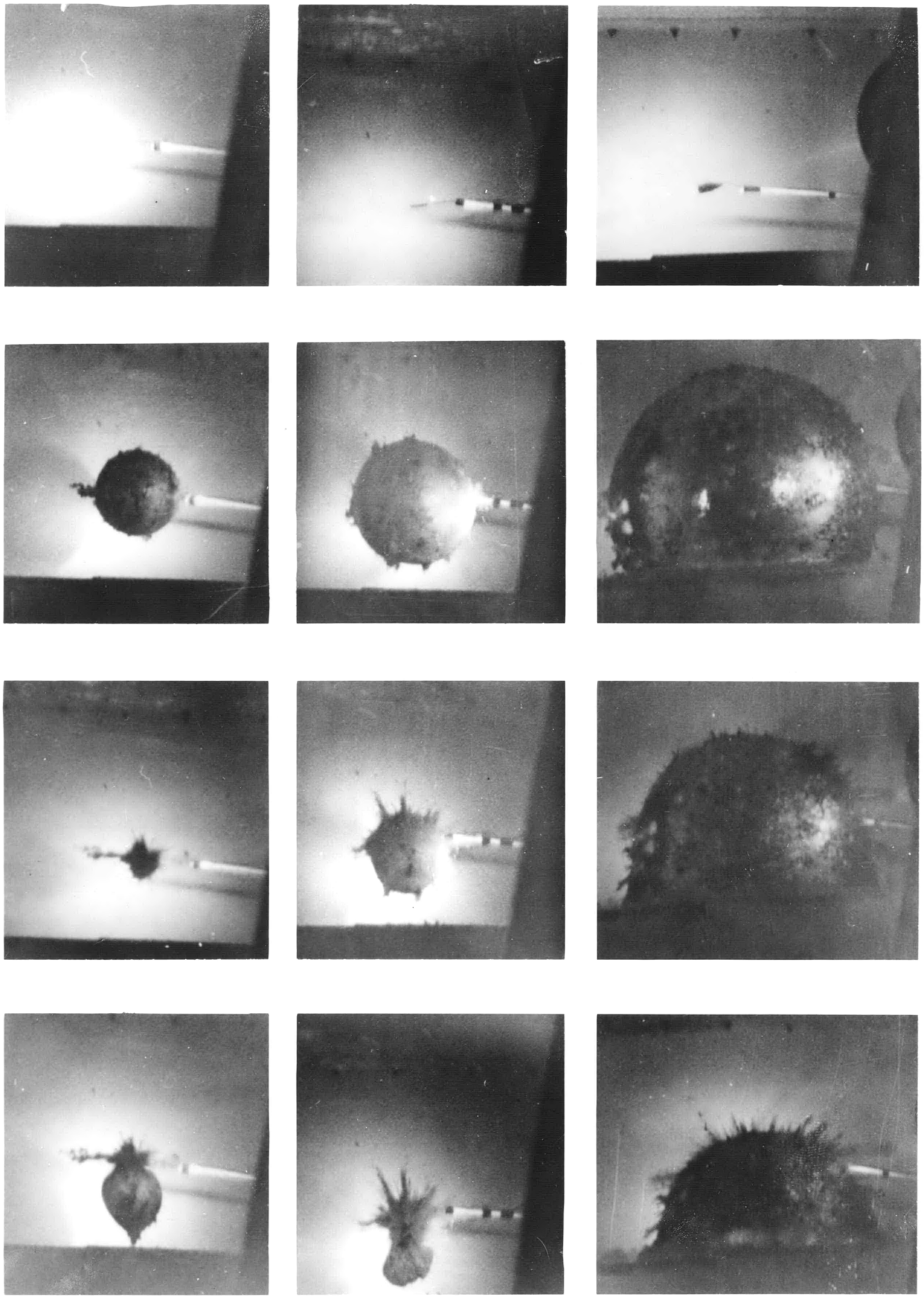
Figure 30 - Curves of Size and Position of the Gas Globe formed from a Number 8 Detonator at Various Depths below the Free Surface of Water 36 inches Deep over Hard Bottom

(Text continued on page 56)

1 The detonator charge is at the right of the picture, lying horizontally.	1 The Mark 1 Modification 1 mine detonator is at the right of the picture, lying horizontally.	1 The 1/2-ounce tetryl charge is at the right of the picture, lying horizontally.
2 0.012 second after the flash. This is near the first maximum expansion.	2 0.016 second after the flash. This is near the first maximum expansion.	2 0.028 second after the flash. This is near the first maximum expansion.
3 0.023 second after the flash. This is the compression peak at the end of the first cycle.	3 0.029 second after the flash. Compression proceeding.	3 0.041 second after the flash. The spherical form is maintained in spite of interference at the bottom.
4 0.034 second after the flash. This is the second maximum expansion.	4 0.032 second after the flash. Compression nearly complete.	4 0.051 second after the flash. Compression proceeding. The center of the sphere is now near the bottom.
Figure 31a - Charge is a Number 8 Detonator	Figure 31b - Charge is a Mark 1 Modification 1 Mine Detonator	Figure 31c - Charge is 1/2 ounce of Tetryl detonated by a Number 8 Cap

Figure 31 - High-Speed Photographs of Gas Globes from Charges of Three Different Weights

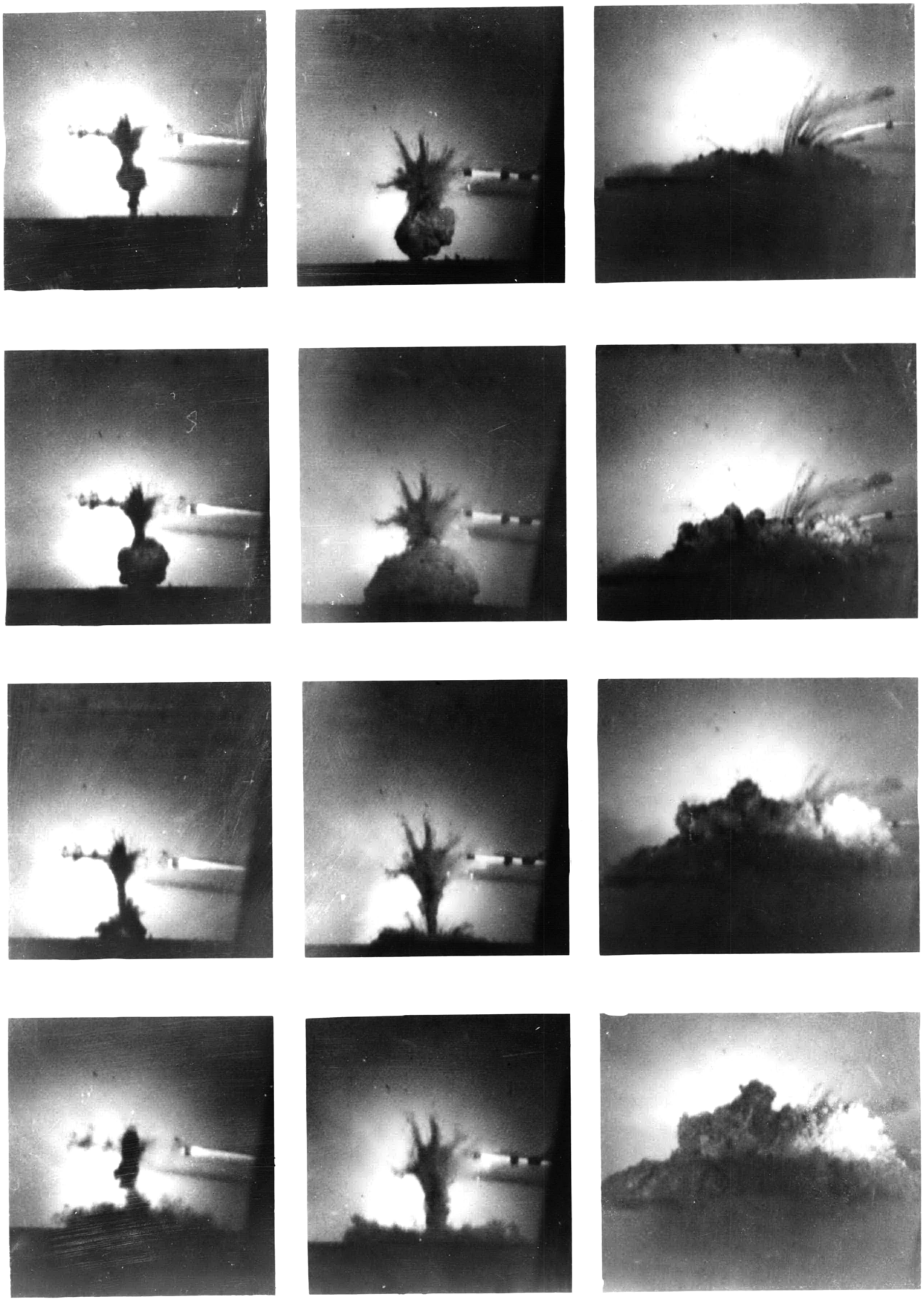
Since exact information as to time is not available, the times given are approximate. Each charge was 10 1/2 inches above the bottom and 23 inches below the boat.



5 0.038 second after the flash. This is the second contraction.	5 0.034 second after the flash. The globe is just contacting the bottom.	5 0.07 second after the flash. The gas globe has collapsed onto bottom.
6 0.044 second after the flash. The globe comes into contact with the bottom.	6 0.043 second after the flash. This is the third maximum expansion.	6 0.08 second after the flash.
7 0.054 second after the flash. This is the third contraction.	7 0.066 second after the flash. The gas globe has ceased to pulsate and is spreading along the bottom.	7 0.09 second after the flash. Pulsation is complete. Gas is expanding and moving toward the water surface.
8 0.3 second after the flash. The globe is starting to break up on the bottom.	8 0.1 second after the flash. Gas is starting to move toward the water surface.	8 0.10 second after the flash.
Figure 31a - Charge is a Number 8 Detonator	Figure 31b - Charge is a Mark 1 Modification 1 Mine Detonator	Figure 31c - Charge is 1/2 ounce of Tetryl detonated by a Number 8 Cap

Figure 31 - High-Speed Photographs of Gas Globes from Charges of Three Different Weights

These photographs are continuations of the three series of Figure 31 preceding.



The curves of size and position for the cases shown in Figure 31, a, b, and c, are given in Figure 32, a, b, and c. The data for these cases are summarized in Table 4. The total quantities of explosive in each of these three cases are as follows:

		Weight grams
Number 8 Detonator:	Tetryl	0.42
	Lead Azide	0.16
	Ground Pyro	0.07
	Potassium Chlorate	0.03
	Lead Salt	0.03
Mine Detonator:	Fulminate of Mercury	4.21
1/2 ounce Tetryl plus Number 8 Detonator:	Granulated, density about 1.0	13.3 as above

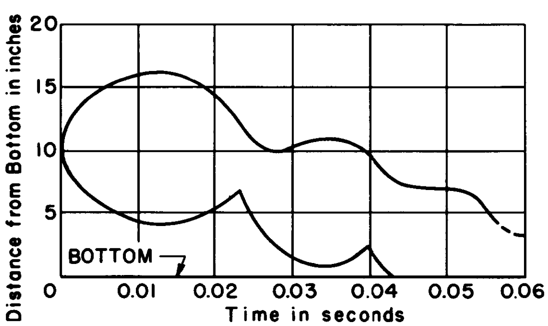


Figure 32a - Charge from Number 8 Cap

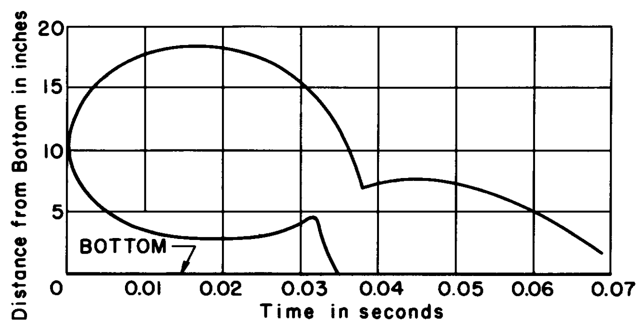


Figure 32b - Charge from Mark 1 Modification 1 Mine Detonator

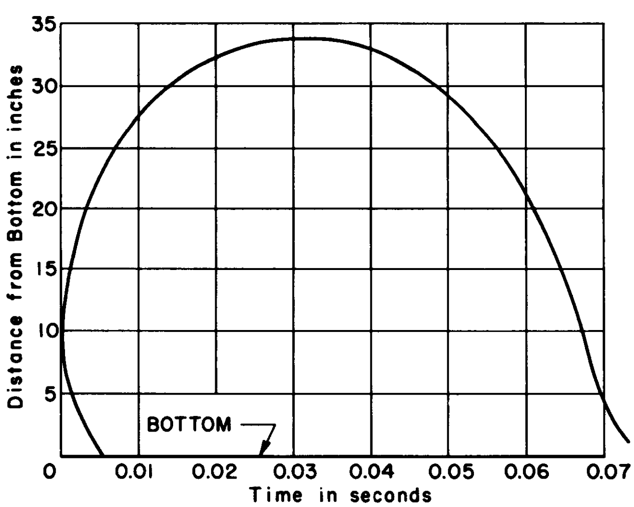


Figure 32c - Charge from 1/2 ounce Tetryl

Figure 32 - Curves of Size and Position of the Gas Globes formed by the Three Different Charges

The charges were placed at a depth of 23 inches under the free surface of water 33 1/2 inches deep over a hard bottom.

The firing of these three charges of different weights under similar conditions permits setting up a tentative list of equivalents. These equivalents are given in Table 5.

TABLE 4

Summary of Data Relating to Explosives in Free Water at Various Depths over Hard Bottom

Charge	Figure	Distance over Bottom inches	Max. Dia. of First Expansion inches	Time of First Cycle seconds	Max. Dia. of Second Expansion inches	Time of Second Cycle seconds	Max. Dia. of Third Expansion inches	Time of Third Cycle seconds
Depth of Water - 36 inches								
No. 8 Detonator	26	0	11.2	0.027	5.6	0.017		
No. 8 Detonator	27	18	11.0	0.023	8.1	0.020		
No. 8 Detonator	28	33	11.0	0.020	12.0	No definite pulsation		
No. 8 Detonator	29	35		Vented through surface				
Depth of Water - 33 1/2 inches								
No. 8 Detonator	31a	10 1/2	11.8	0.024	10.0	0.017	7.3*	0.016*
Mk 1, Mod 1 Mine Detonator	31b	10 1/2	15.3	0.033	7.1*	0.036*		
1/2 ounce Tetryl	31c	10 1/2	46*	0.070*				

* Globe is in contact with bottom.

TABLE 5

Equivalent of Small Charges in Terms of Tetryl

	Maximum Volume of Gas Globe on First Pulse cubic inches	Total Weight of Explosive grams	Equivalent Weight* of Tetryl grams
Number 8 Blasting Cap	860	0.71	0.24
Mine Detonator	1 875	4.21	0.52
1/2 ounce of Tetryl	50 970	14.0	14

* By equivalent weight is meant the weight of tetryl which would evolve a quantity of gas in strict proportion to the weight of gas.

5. Explosion between Parallel Plates

On firing a Number 8 cap at mid-distance between plates separated by 15 inches or more, the gas globe expands and contracts very much the same as in the free-water condition. Frames from the motion pictures, Figure 33, show the action of charges exploded between plates spaced 24 inches apart. The disposition of the plates is as shown in Figures 5a and 5b, page 6.

1

Before the explosion the Number 8 blasting cap is suspended midway between two vertical steel plates 24 inches apart.

2

0.010 second after the flash. The gas globe is near its first maximum expansion.

3

0.022 second after the flash. This is the end of the first cycle. The bright points to the right of the globe are thought to be portions of the container which were left behind during the inflow phase, just as the bent end of the ignition wires remains where the outflow put it.

4

0.030 second after the flash. This is the second maximum expansion.

5

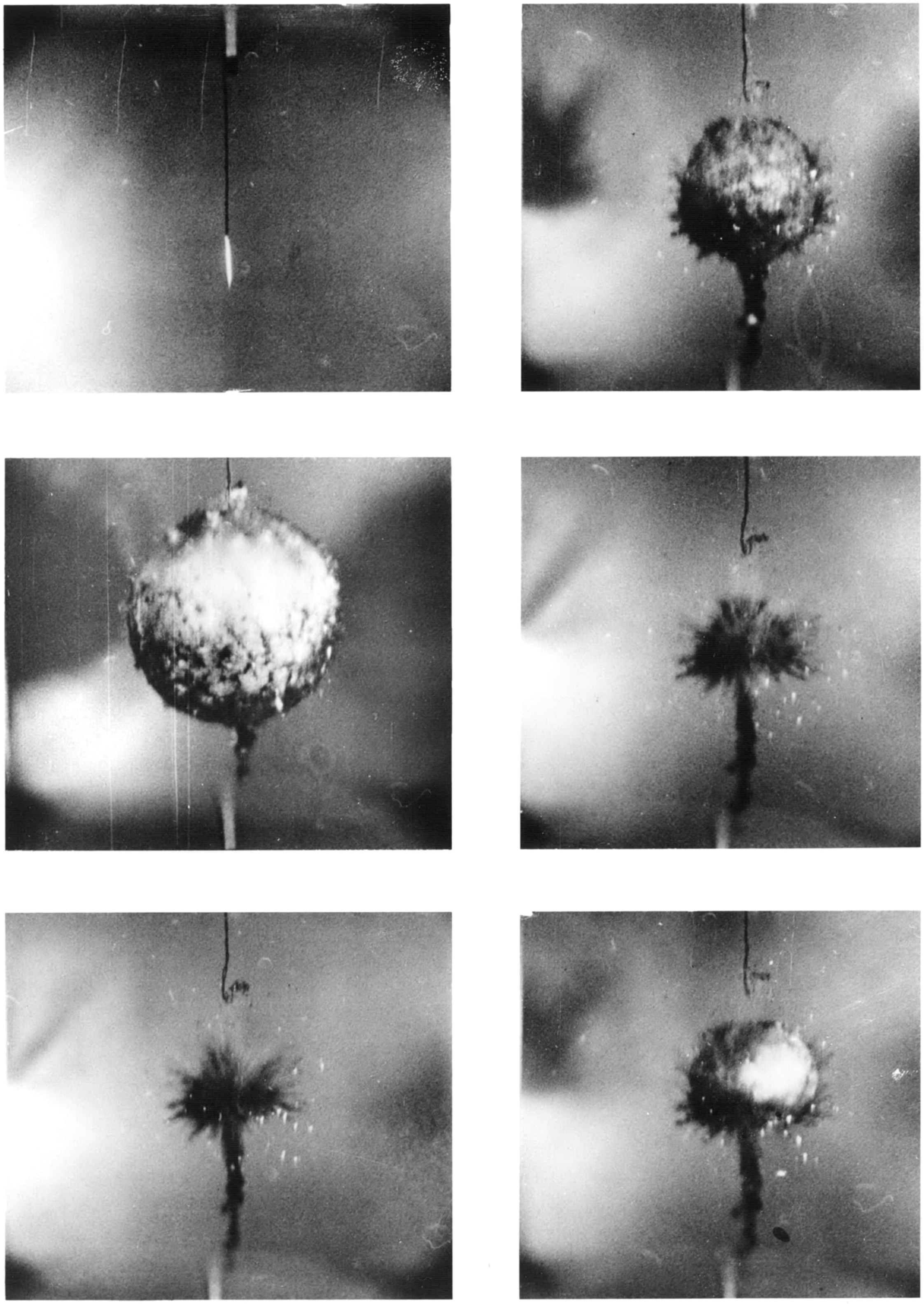
0.039 second after the flash. This is the second contraction. The protuberance has the usual appearance.

6

0.044 second after the flash. This is the third maximum expansion. The globe is no longer perfectly spherical.

Figure 33 - High-Speed Photographs of a Charge Fired between Two Parallel Vertical Plates

The plates were here separated by a horizontal distance of 24 inches.



1
The Number 8 blasting cap is suspended midway between vertical parallel steel plates 12 inches apart.

2
0.012 second after the flash. This is the first maximum expansion, which carries the globe almost to contact with the plates.

3
0.020 second after the flash. The gas globe is elongated horizontally during the compression stroke.

4
0.021 second after the flash. The original globe is dividing into two globes.

5
0.022 second after the flash. The original globe has now divided in two. The protuberance is normal.

6
0.023 second after the flash. This is the compression peak. The two globes have contracted separately.

7
0.024 second after the flash. The two globes now expand in contact with the side plates.

8
0.027 second after the flash.

9
0.028 second after the flash.

10
0.033 second after the flash. The two globes have now reached full expansion in the second cycle, and are hemispherical.

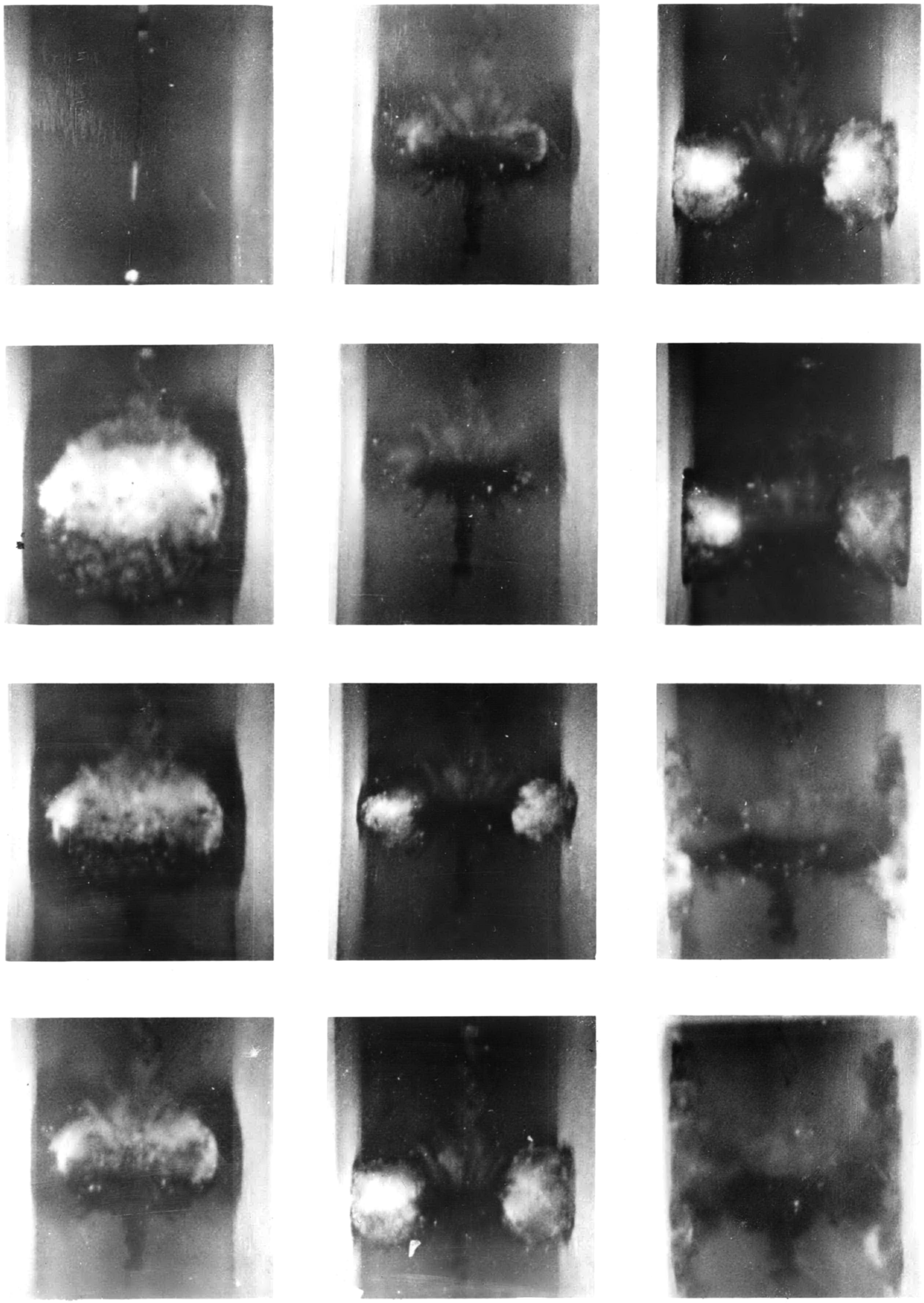
11
0.062 second after the flash. Each of the two globes delivers a blow to its plate.

12
The two globes have flattened themselves out against the two plates, leaving some of the products of combustion in the center.

Figure 34 - High-Speed Photographs of a Charge Fired between Two Parallel Vertical Plates

The plates were here separated by a horizontal distance of 12 inches.

When the charge was fired midway between the plates separated by 12 inches, the globe expanded spherically outward to a maximum diameter of 10.6 inches, as shown in Figure 34. This expansion required 0.012 second. As the compression stroke set in, the globe ceased to stay spherical. The diameter parallel to the plates contracted more rapidly than did the diameter perpendicular to the plane of the plates. 0.022 second after the detonation, the globe divides in the middle and a small globe expands onto each plate.



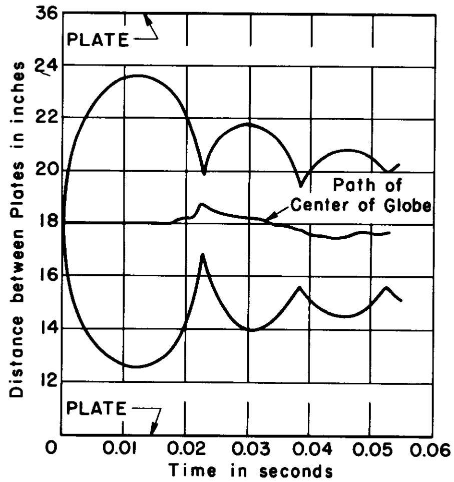


Figure 35a - Plates separated by 36 inches

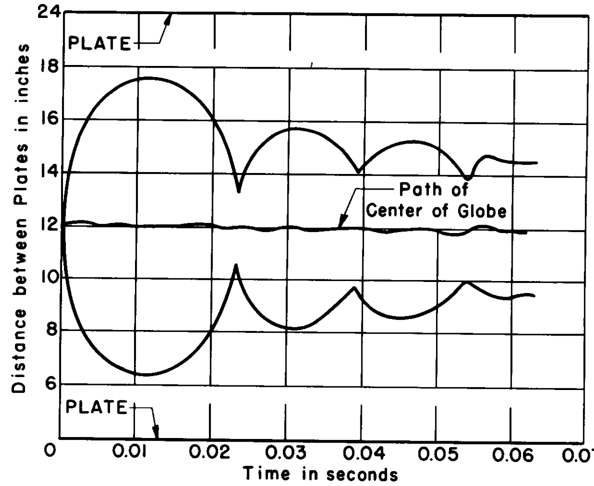


Figure 35b - Plates separated by 24 inches

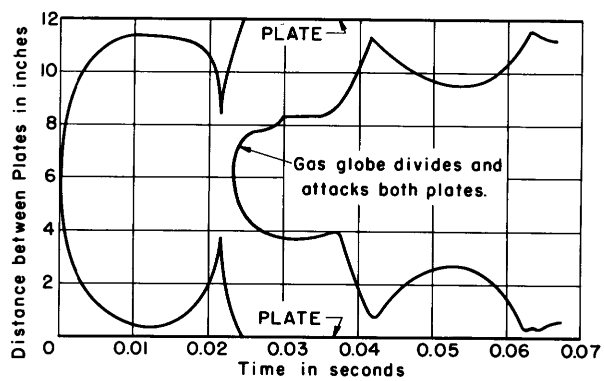


Figure 35c - Plates separated by 12 inches

Figure 35 - Curves showing Diameter and Movement of a Gas Globe from a Charge Fired between Two Parallel Vertical Plates

Curves of size and position against time for these cases are given in Figure 35, a, b, and c. It was found that unless the cap was placed exactly midway between the plates the globe would move toward the nearest plate within limits that are critical. Thus, with the plates separated by 18 inches it was found that one quarter inch off center was enough to start the globe toward the side.

CONCLUSIONS

The data of this paper are exploratory in nature; they demonstrate an unsuspected intricacy in the phenomena attending a small-scale underwater explosion. Although it is found that the repetitive nature of an underwater explosion has been known to isolated persons for a long time, even to Abbott in 1864, the consequences of this fact have not even yet been evaluated, and an adequate theory is not even yet available.

These consequences must be very important, it is not possible to assume that the whole action of an explosion on a target can be expressed in terms simply of the position at which the charge is fired. Until the contrary is proved, the migration of the explosive center must also be taken into account.

There are three limitations on this conclusion which together permit a continuation of work along earlier lines pending better understanding of the pulsation and migration of the gas globe.

1. Since similitude between model and full-scale explosions is in any case doubtful, small-scale work is accepted only for qualitative conclusions, and larger-scale models and full-scale structures still must be relied upon for first-hand design data.

2. In particular, since in small-scale tests the atmospheric pressure remains unaltered, the total pressure against which a small-scale gas globe expands is greater than similitude would require. The maximum expansion of the globe is thus proportionately greater in service than in the tests herein reported, and the limiting depth at which the globe blows through the surface is greater on full scale than the small-scale tests indicate.

3. There is still no good reason to believe that any distant explosion can do more damage than the same charge at smaller distance. The contact explosion is still the most effective, and in this case migration of the globe can hardly be significant.

For these reasons the time has not yet come for trying to introduce the pulsation of the globe as a consideration in the processes of practical structural design.

At the same time this report presents convincing evidence of a fact of general application. The high pressures and accelerations involved determine that the motion of a given local mass of water is determined wholly by the direct action of forces on that mass, and the transmission of such action to more distant masses, as in ordinary flow does not occur. Thus during the first expansion the gas globe accurately retains its spherical form in any one sector without disturbance by interfering action in another sector. And venting upward has little or no effect on expansion of the globe downward or horizontally. Equalization of action in different directions which is complete in the static case, and modified as shown by the pitot gage in flow about a ship, is absent in the case of the explosion. Until the pulsating action of the explosion has been reduced to calculation, this must remain the chief practical result of the present report.

On the other hand, the photographs herewith presented make it very clear that no theory of underwater explosive action can have a chance of acceptance unless it takes account of the consequences of pulsation and migration of the gas globe. In particular, it is not permissible to assume that the effect of an underwater explosion in causing damage to an adjacent structure is limited to what is transmitted by the shock wave, or even by the whole action during the initial expansion of the globe.

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(3) "Experimental Torpedo Caissons, Status of Instrumentation," 016012, April 1941. Confidential motion pictures made at the Norfolk Navy Yard in connection with this report are filed at the Bureau of Ships under the title, "Multiple Impact (Cruiser Model, Shock Test of Three Blowers, etc.)"

(4) "Underwater Explosions. Time Interval between Successive Explosions," A/S F3 British Secret Report, February 1941, WA-47-21. This unsigned report from Fairlie is thought to be that referred to by the name of Willis.

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

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(8) "Handbuch der Experimentalphysik," W. Wien and F. Harms, vol. IV, Part 1, 1931, pp. 94-119, Chapter II "Spezielle Strömungsformen und ihre Dynamik," (Special Types of Flow and their Dynamics); Section 3 "Potentialströmungen im allgemeinen und als Beispiel Bjerknes' pulsierende Kugeln," (Potential Flow in General and Bjerknes' Pulsating Spheres as an Example); (b) "Bjerknes pulsierende Kugeln," (Bjerknes' Pulsating Spheres).

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