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

A STUDY OF THE SURFACE EFFECTS CAUSED BY AN UNDERWATER EXPLOSION

PART 1

1750 POUNDS OF TORPEX NEAR THE BOTTOM IN 40 FEET OF WATER

by

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and
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PERSONNEL

This test was conducted by personnel from the U.S. Naval Mine Warfare Test Station, Solomons, Md.; the Naval Ordnance Laboratory; the Bureau of Ordnance; and the David Taylor Model Basin. R.B. Baxter and W.A. Lovell of the Taylor Model Basin performed the pressure measurements and C.H. Bradley and C.W. Wyckoff took the motion pictures. The data were analyzed by Lieutenant D.C. Campbell, USNR, and the report was written by Lieutenant Campbell and Captain H.E. Saunders, USN.

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PART 1

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ABSTRACT

A charge of 1750 pounds of Torpex was fired one foot off the mud bottom of the Patuxent River in 40 feet of water. A time history of the dome and the plume are given as obtained from high-speed motion-picture records. Oscillographic pressure measurements give related times of detonation and gas-globe collapse.

INTRODUCTION

Considerable study has recently been given, both in the United Kingdom and in the United States (1) (2) (3) (4) (5) (6),* to the surface effects produced by an underwater explosion, in an effort to derive from them a reasonably close estimate of the depth of the charge and the power developed. Surface effects have also been studied to learn more of the phenomena accompanying an underwater explosion; the present study has been undertaken specifically for this purpose. It is intended as only the first of a number of studies which will be carried out by the staff of the David Taylor Model Basin in the near future.

However, this study is unique in that it utilizes motion-picture records taken at a rate of 1600 frames per second, yielding data over much shorter intervals than the records of any other large-scale explosions for which published data can be found.

GENERAL FEATURES OF TEST

The test described in this report was one in which 1750 pounds of Torpex was fired just clear of the bottom in 40 feet of water. The test was conducted on 2 March 1944 in a wide stretch of the Patuxent River off Sotterly Point, about 8 miles above Solomons, Maryland. Figure 1, copied from a chart of the vicinity, shows the area of water in the vicinity and the soundings near the site.

The charge was suspended 1 foot clear of the bottom in 40 feet of water. It was intended to simulate the explosion of a ground mine in this test, without the uncertainty of having the mine sink to an undetermined depth in the mud. The bottom in this locality was of soft mud, in which a

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* Numbers in parentheses indicate references on page 16 of this report.

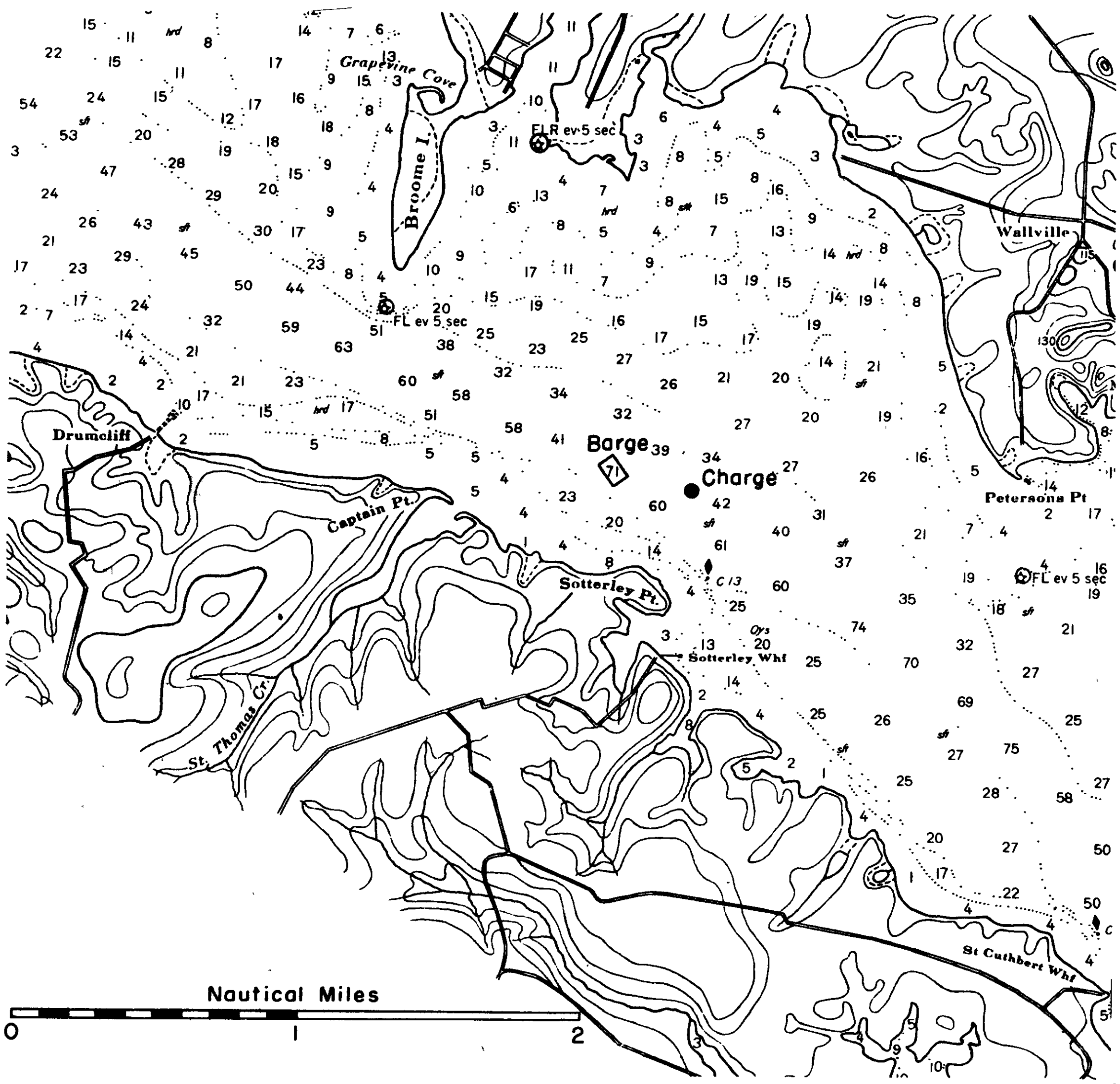

Figure 1 - Chart of the Vicinity of the Explosion in the Patuxent River

This figure was copied from U.S. Coast and Geodetic Survey Map of the Patuxent River, Solomons, Md.

diver would sink 3 or 4 feet before coming to rest with his feet on firm ground. In this case the depth of the soft material was determined by sounding with a weighted wooden box, which served also as an excellent improvised current meter.

To buoy up the charge and to carry a rather extensive series of underwater gages of various kinds, as described elsewhere (7), a wooden spar about 80 feet long was made up, to float at the surface. The charge was suspended from this spar at midlength, and additional buoyancy was provided by a number of spherical buoys 32 inches in diameter lashed to the spar at several points along its length.

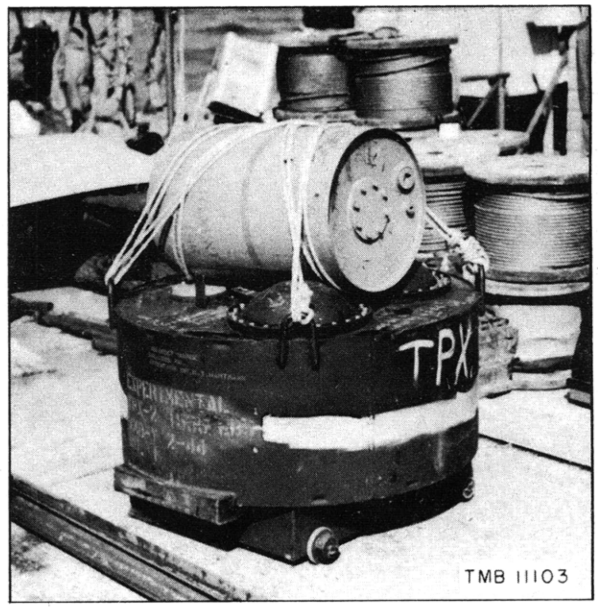

Figure 2 - The Charge, Containing 1750 Pounds of Torpex

The lower cylinder is a Mark 18 mine case. The upper cylinder is a Mark 6 depth charge lashed to the top of the mine case. About half of the upper cylinder was empty of explosive and filled with air.

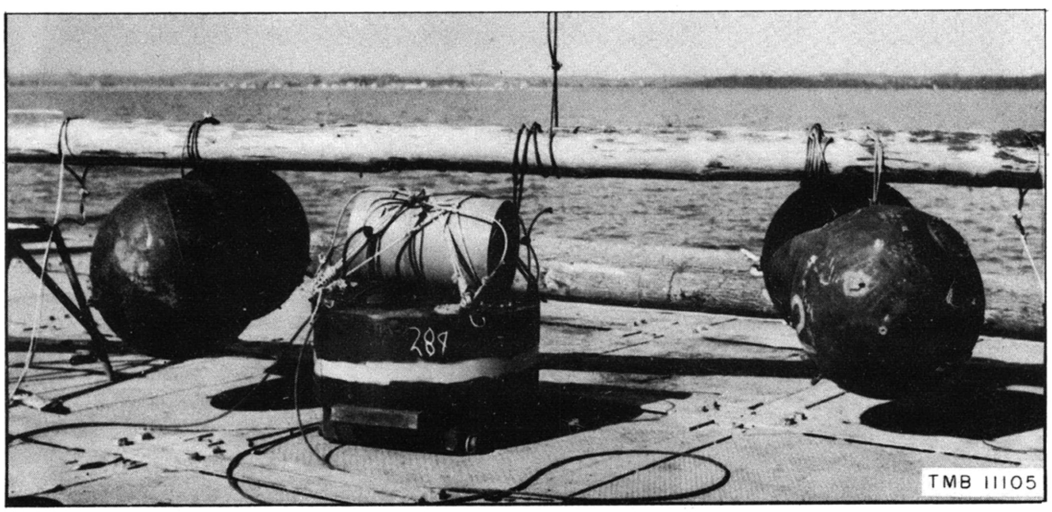

Figure 3 - The Charge and Some of the Rigging Used in Its Anchorage

This view shows the central portion of the wooden spar with four of the buoys. Clusters of Hilliar and momentum gages were also suspended from this rigging.

The charge was so large that it had to be loaded in two containers, as shown in Figures 2 and 3. The detonator and the booster were in a depth-charge case, on the top of a mine case. It was considered that if only the upper charge exploded, the fact would be evident from the relatively slight effects of the small charge.

TEST APPARATUS

Photographic records were made with one high-speed Jenkins camera equipped with a rotating disk carrying 48 matched lenses, and with two

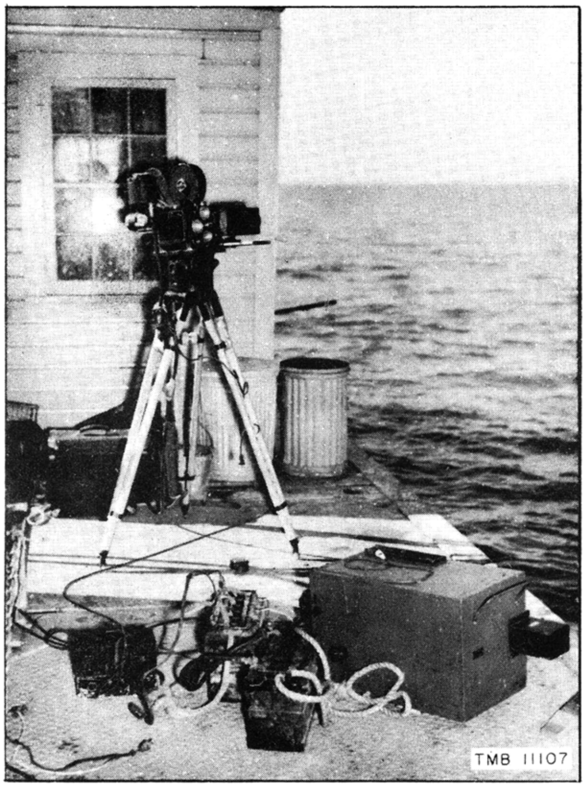

Figure 4 - The Camera Setup on the Barge

The TMB Mitchell camera is at the upper left of the picture and the Jenkins camera in the right foreground, on the deck of the barge. The Mitchell camera ran at 24 frames per second and the Jenkins camera ran at 1600 frames per second. They derived their power from storage batteries. In the left background is a house in which the oscillographic measurements were made.

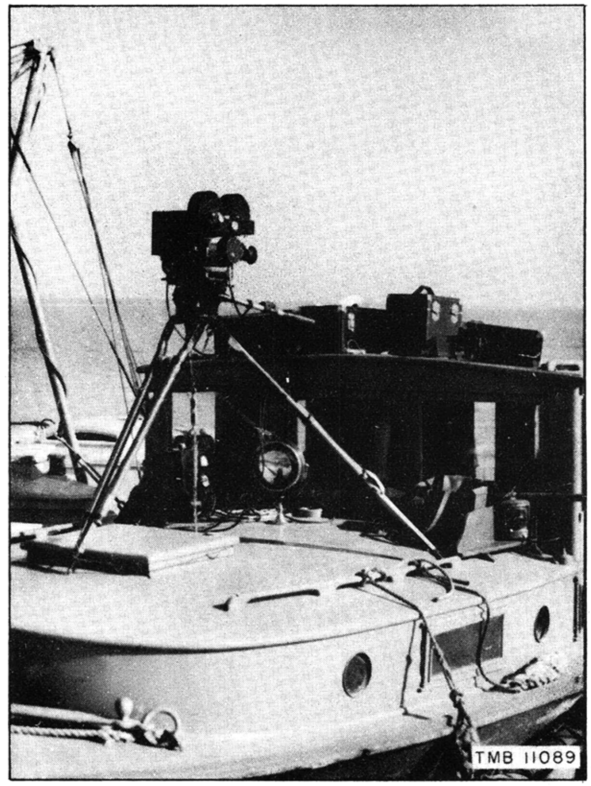

Figure 5 - The NOL Mitchell Camera on the Deck of a Small Boat

To the rear of the hatch on the deck of the boat is a gasoline-driven motor-generator set which furnished power for the camera motor. This camera accelerated from 60 frames per second to 100 frames per second during the explosion.

Mitchell motion-picture cameras. One Mitchell camera and the Jenkins camera were mounted on a barge, as shown in Figure 4, anchored about 1000 feet from the charge; these cameras were operated by TMB personnel. The other Mitchell camera, operated by personnel of the Naval Ordnance Laboratory, was mounted on the forward deck of a small boat, as shown in Figure 5. The boat was more than 1000 feet from the charge and at some distance from the barge, as shown in Figure 6. The TMB Mitchell camera on the barge ran at 24 frames per second, and the NOL Mitchell camera on the boat accelerated from 60 to 100 frames per second during the explosion; the Jenkins camera ran at approximately 1600 frames per second.

The Jenkins record was timed by a stroboscopic, high-voltage spark discharge which fogged a small spot on the film. Normally these timing pulses are separated by 0.01 second but the operation was erratic during the early

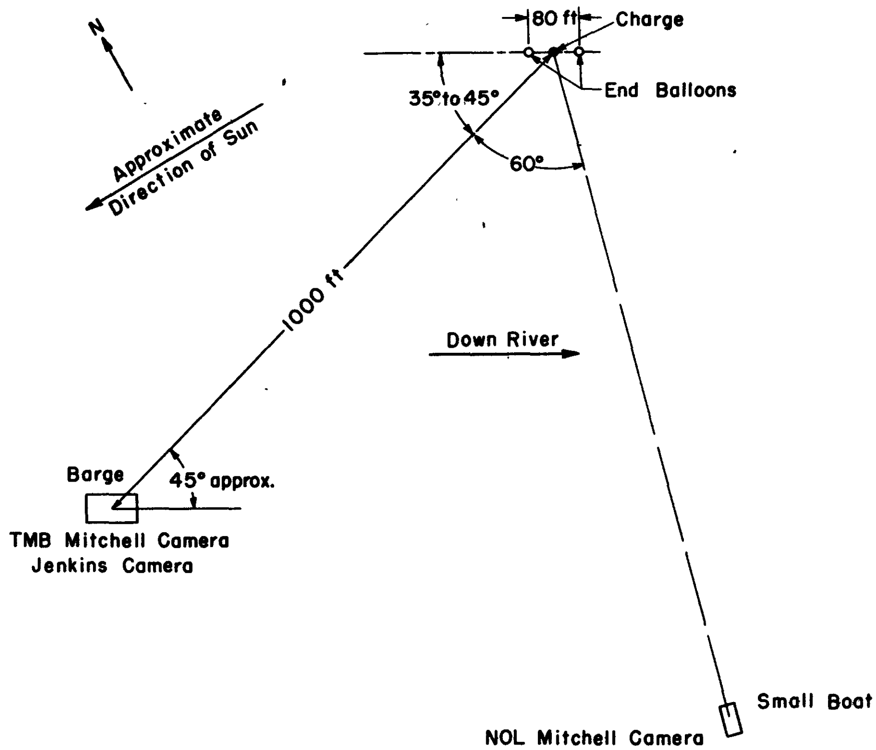

Figure 6 - Diagram Showing the Position of the Barge, the Small Boat, and the Charge

part of the explosion record and it did not become regular until the latter part of the record.

To determine accurately the instant at which detonation occurred, to record this instant on the motion-picture film, and to determine the time between pulses, a piezoelectric pressure gage was suspended in the water from the barge upon which the TMB Mitchell and Jenkins cameras were mounted. The signal from this gage was taken to a string oscillograph mounted on the barge, and the oscillograph record was timed by a chronometer which closed an electric circuit to give the oscillograph a pulse every half second.

The oscillograph was also connected to the Jenkins camera timer, so that by comparing the camera timing pulses with the timing pulses from the chronometer a fairly accurate time scale was established, as shown in Figure 7.

To provide a scale in the photographs, four 3-foot meteorological balloons inflated with helium were allowed to float in the air over the charge location, as illustrated in Figure 8. By taking into account a foreshortening angle of 45 degrees,* a scale was obtained from which the film data could

* The angle between a horizontal line through the balloons and the line of sight was somewhere between 35 and 45 degrees.

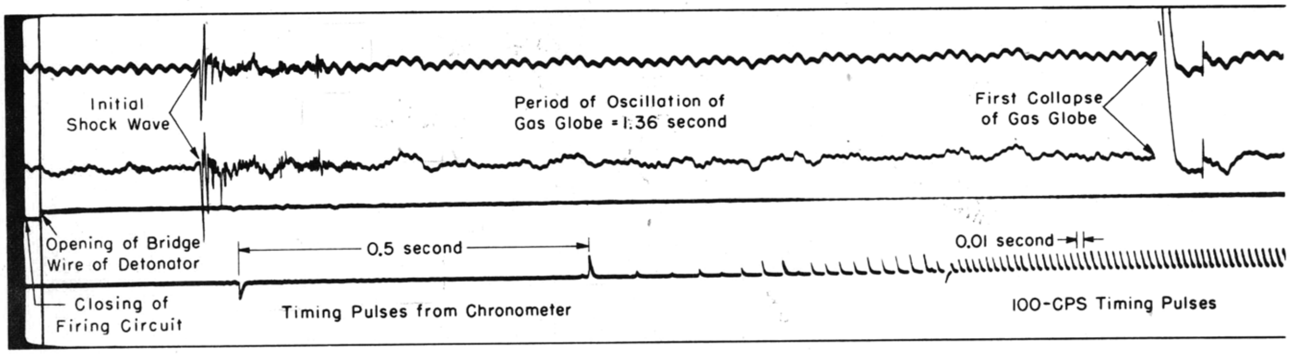

Figure 7 - Oscillograph Record from the Explosion of 1750 Pounds of Torpex

This record shows two time-pressure measurements taken in water 1000 feet from the explosion. The 0.5-second timing pulses are from a chronometer and the stroboscopic timing pulses are from the Jenkins camera timer.

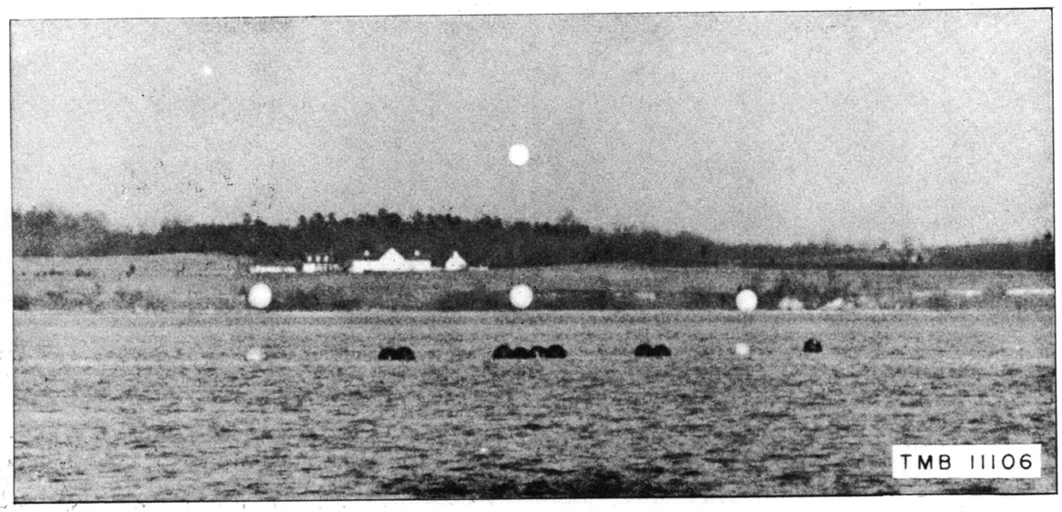

Figure 8 - Balloons in the Air over the Charge

Four 3-foot meteorological balloons floated in the air over the charge location to furnish a scale in the photographs. The distance between the two end balloons was 80 feet.

be converted to full scale. This scale factor was checked by using the optical system of the camera and a camera-to-charge distance of 1000 feet. Agreement was found to be good.

TEST PROCEDURE

Before the explosion a timing run was made with the Jenkins camera so that a curve of film speed as a function of time and length of film could be made. The stroboscopic timing equipment operated satisfactorily during this test, as shown by the curve in Figure 9. During the run involving the actual explosion the stroboscopic timer did not start until more than 0.5 second after the start of detonation. It was therefore necessary to use data

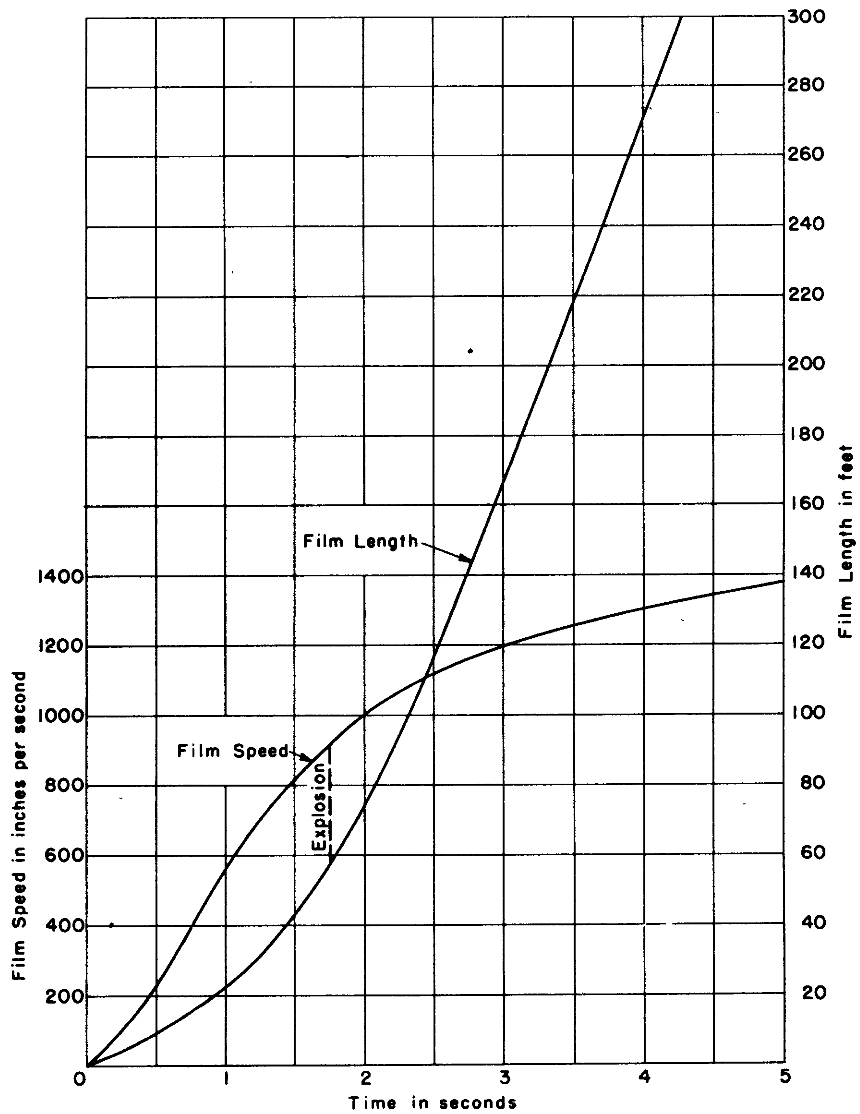

Figure 9 - Record of Film Speed in Jenkins Camera

This record gives a relationship between the film speed, the time, and the film length in feet. It was made in the Jenkins camera in a timing run just before the explosion.

from the timing run and the oscillograph record to obtain the timing of the pictures from the Jenkins camera.

TEST RESULTS

As is usual for charges fired under these conditions, the above-water action occurred in two distinct phases: the spray dome, and the plume. These phases were so distinct as to be visible to the observers and to be plainly evident in the motion pictures, perhaps more so than in photographs of explosions of smaller charges.

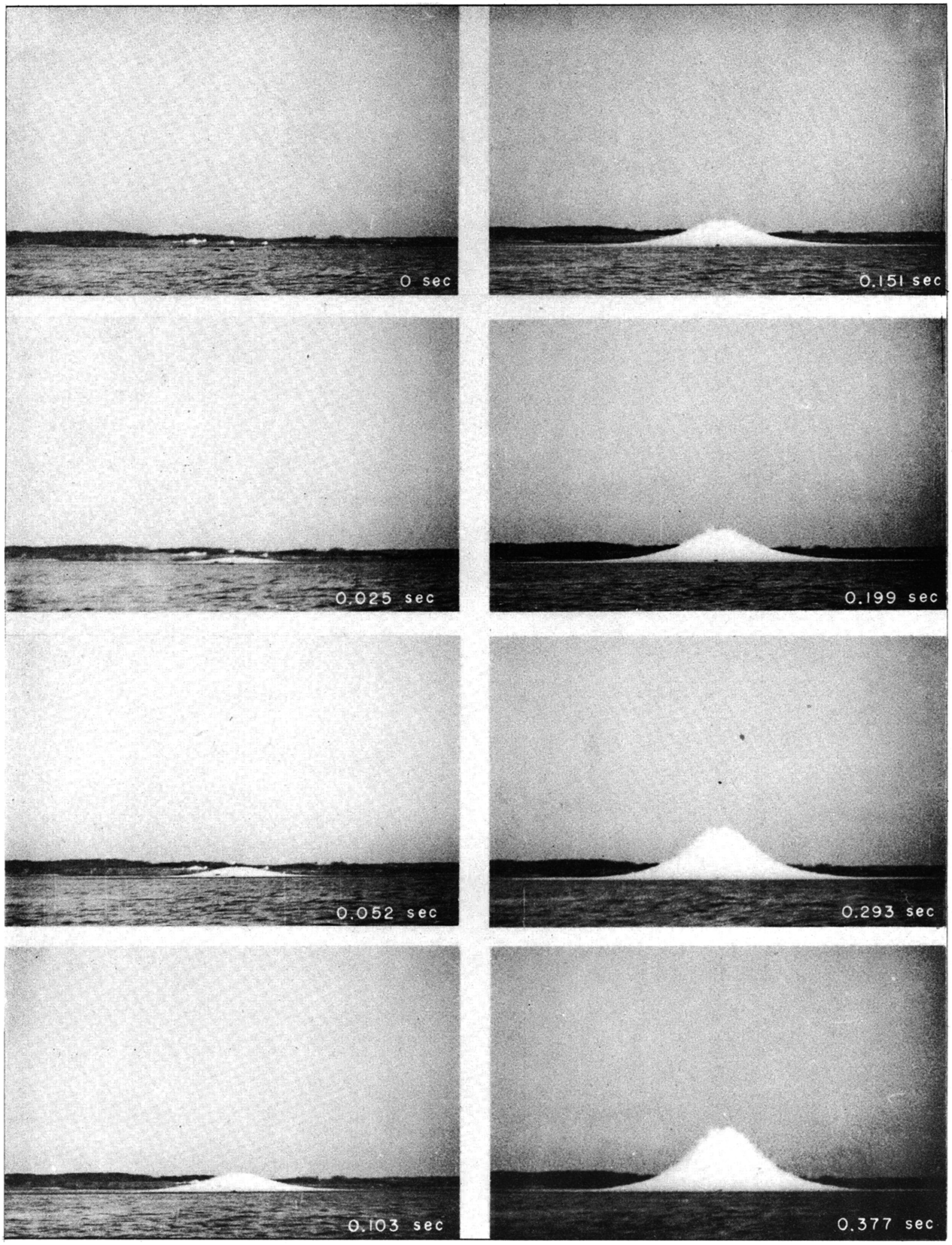

Figure 10 - Growth of Spray Dome and Plumes from an Underwater Explosion

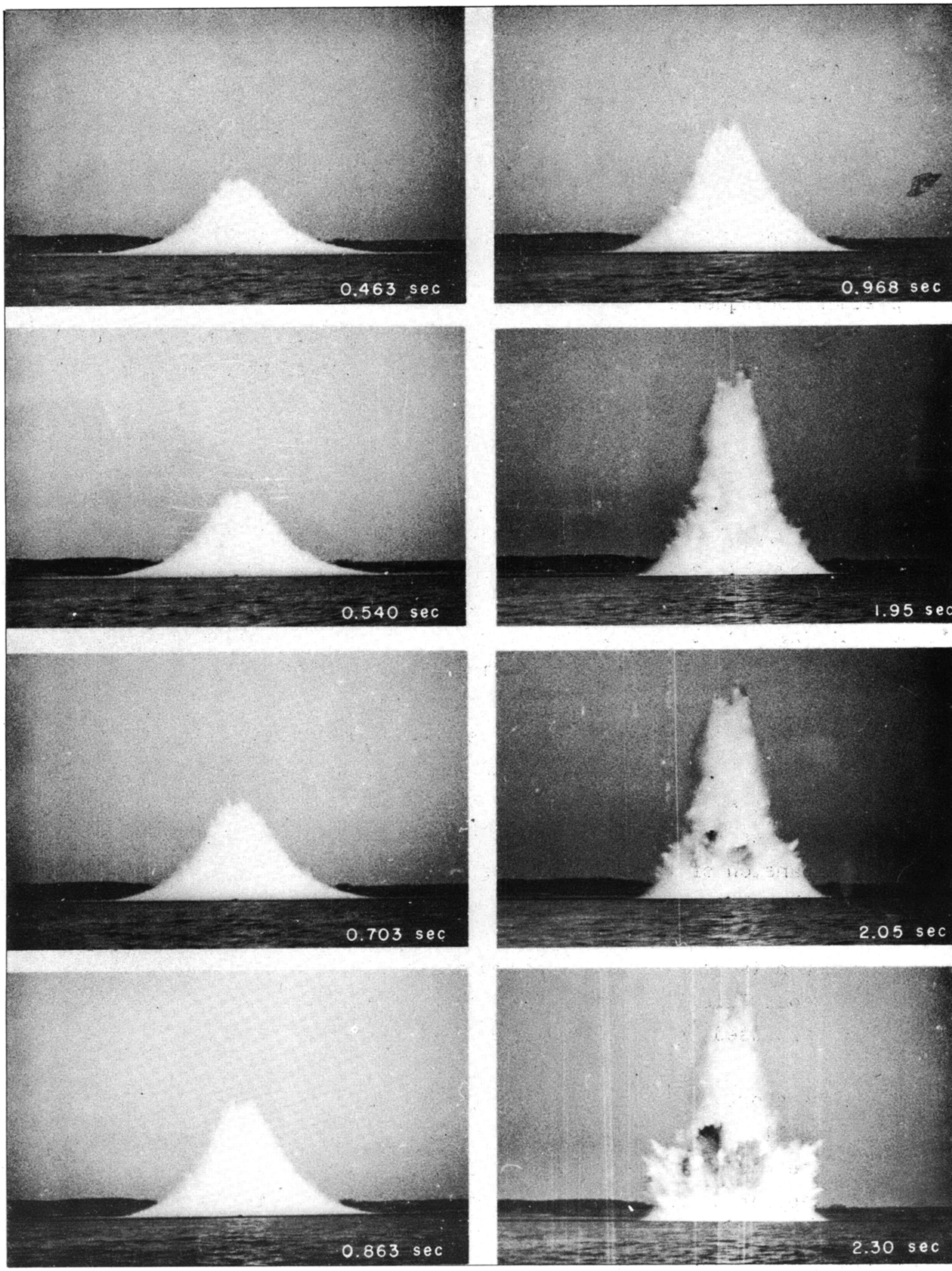

Figure 10 - Growth of Spray Dome and Plumes from an Underwater Explosion

The photographs are enlarged frames selected from a high-speed motion picture of the underwater explosion of 1750 pounds of Torpex near the bottom in 40 feet of water. The motion-picture record is filed at the Taylor Model Basin under File FV-18.

The records and the analysis in this report were made from the Jenkins-camera record. The two Mitchell records are interesting to view as motion pictures but they were not used for analysis.

Full detonation of both parts of the charge occurred. The visible spray dome was 140 feet in diameter when it first formed; at the end of 1 second it was 240 feet in diameter and more than 110 feet high. At its peak, about 2.5 seconds after the detonation, it was 215 feet high, but by this time its diameter at the surface had decreased to 190 feet, for reasons to be explained subsequently.

At 1.9 second, plumes shooting out at an angle of about 45 degrees appeared beyond the boundary of the spray dome; some of these plumes were discolored.

ANALYSIS

THE SPRAY DOME

The visible dome, formed by drops of water projected into the air, was preceded by the formation of a dark ring on the surface of the water; this ring shows as almost black in the photographs of Figure 10. It is believed that the impact and reflection of the shock wave at the surface first ruffles the surface with a myriad of small ripples whose sides are so steep and whose crests are so sharp that there is almost no reflection of light from them. The width of this band is very considerable, especially in the early stages. In the photograph marked 0.052 second in Figure 10, it is equal to the radius of the dome proper at the water surface.

Film resolution was not adequate to permit measurements of the velocity of expansion of the shock wave on the water surface.

Although it is not apparent in the reproductions of Figure 10, all the drops of water in the spray dome appear to rise *vertically* in the air. This phenomenon is not a new one by any means (5), but with the exception of studies at Woods Hole it seems to have been given little attention previously. It will be discussed at greater length in a subsequent part of the present report.

The short interval between exposures on the Jenkins-camera film, less than 1 millisecond, permit a fairly accurate determination of the rate of rise of the water bubbles forming the spray dome for all stages of the dome. They appear to have their greatest vertical velocity just over the charge, as may be deduced from the final shape of the dome. The distribution of initial velocity across a radius of the dome, in a horizontal direction, resembles closely the outline of the dome, as may be seen by comparing Figure 11 with the photographs in Figure 10. This velocity curve was obtained from

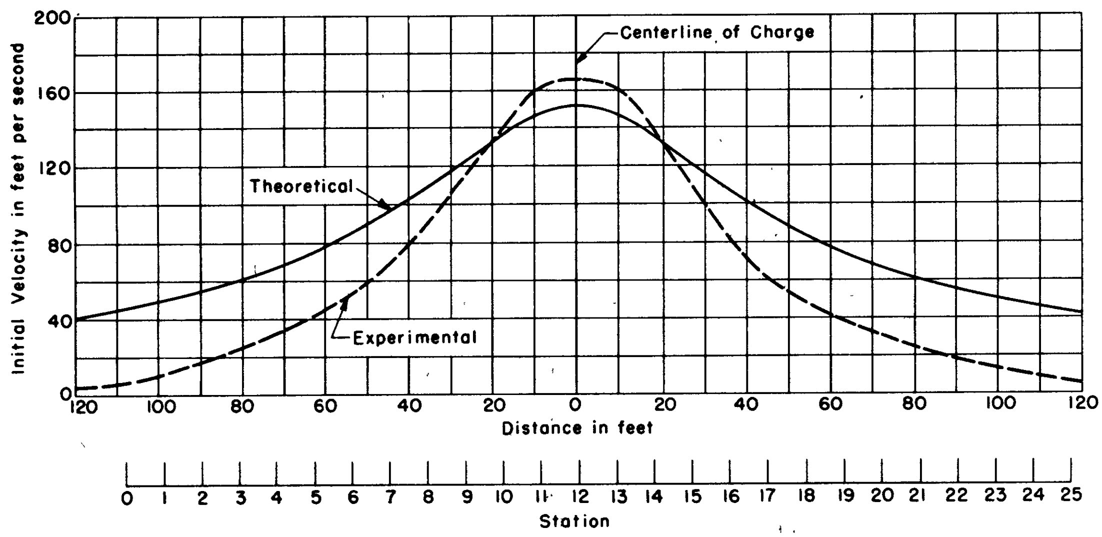

Figure 11 - Initial or Maximum Velocity of Water Surface Resulting from the Explosion of 1750 Pounds of Torpex

A theoretical curve by Kennard and an experimental curve are given.

The initial velocities, used to plot the experimental curve, were obtained from the curves of Figure 12. The curves of Figure 12 are numbered to correspond to the stations.

data derived from the motion-picture records by the use of the well-known gravitational formula

$$S = V_0 t + \frac{1}{2} g t^2$$

where S is the water height at a given time t, and g* is the acceleration of gravity. The unknown is the initial velocity V_0. Since air resistance and various frictional forces act on the water particles in the dome, they do not have the same action as a body falling freely in a vacuum. Therefore, the initial velocities were determined for a number of different times from 0.001 second to 1.000 second, and these were plotted in Figure 12 where they were extrapolated to zero time to give the velocity-distance curve of Figure 11. Also plotted in Figure 11 is a theoretical curve by Kennard.** The two curves are in fair agreement directly above the charge but the experimental curve falls off at a greater rate than the theoretical curve as distances from the charge increase.

A time history of the spray dome was obtained directly from the photographs, and the data were plotted as in Figure 13. The times marked on

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* It will be noted for positions directly over the charge that the decelerating force is 2 1/2 times g for large time intervals, i.e., approximately 1 second.

** The theoretical curve should be described as a curve for the maximum velocity given to the surface of the water by the shock wave. That is, it is not a curve for the velocity of the spray, derived from a theory of spray projection.

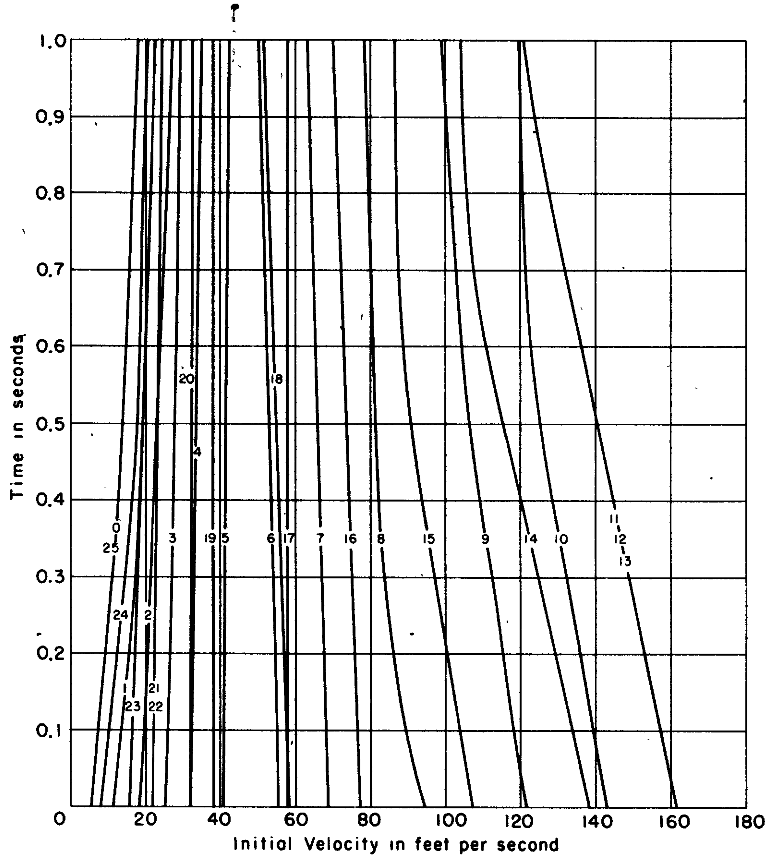

Figure 12 - Variation of Initial Velocity of Water Surface as Calculated from Various Times and Positions

The initial velocities interpolated to zero time are plotted in Figure 11. The numbers on the curves correspond to the stations given in Figure 11.

this plot correspond to the reproductions in Figure 10. Examination of the oscillograph record of Figure 7 shows that the gas globe has a period of oscillation of 1.36 second. The globe must be near its maximum diameter at 0.68 second. Using the figures for TNT (8) in free water, with 10 per cent added for the additional energy of Torpex, a maximum globe diameter of 86 feet is obtained. This is sketched in Figure 13, with the charge position as the globe center. The water in the dome continues to rise after the gas globe has reached its maximum size.

THE PLUME

About 2 seconds after detonation and 0.7 second after the first collapse of the gas globe, plumes appear through the side of the dome, shooting out at angles of about 45 degrees as shown in Figure 13. Some of these plumes are streaked with black in sharp contrast to the white of the spray dome. It has been suggested by Dr. Hartmann (7) that this discoloration is

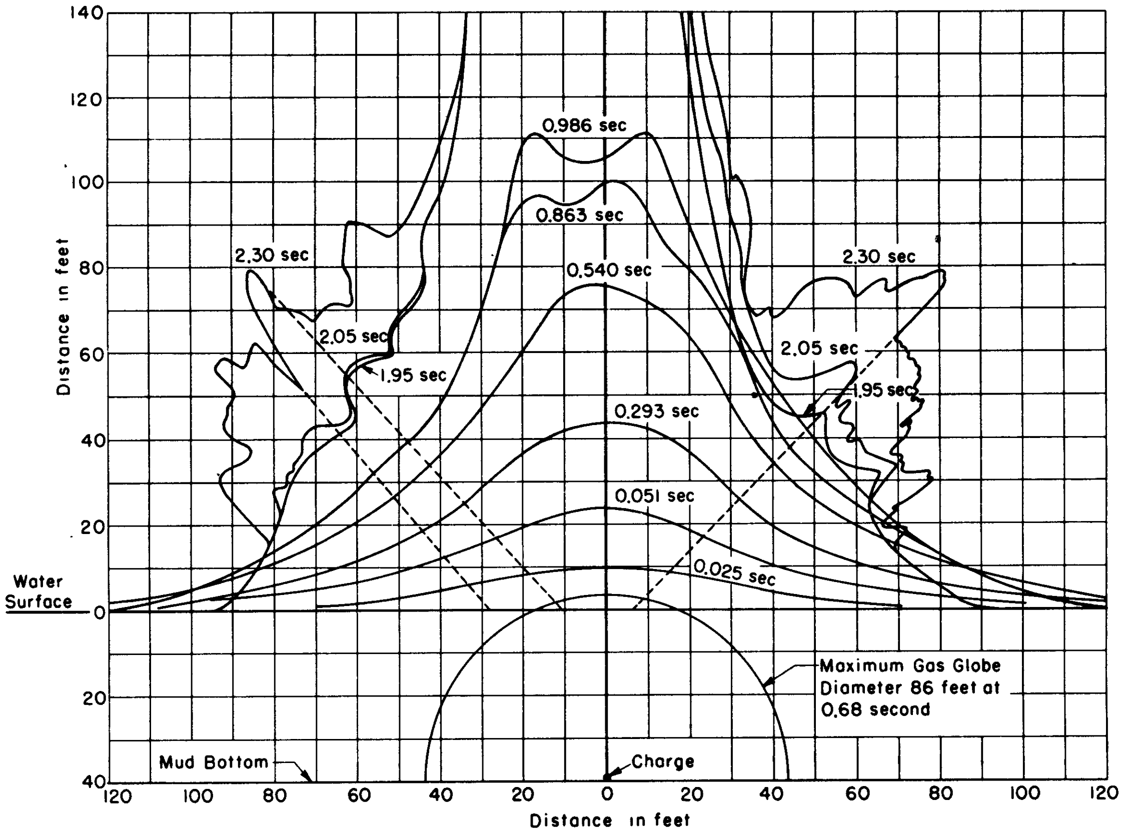

Figure 13 - Time History of Dome and Plume from the Underwater Explosion of 1750 Pounds of Torpex

In free water a charge of this size would produce a gas globe with a maximum diameter of 86 feet, neglecting bottom effects.

The broken lines represent an attempt to trace the plumes to their origin. These lines were obtained by connecting the same point on the plume as it appeared in three successive frames of the motion-picture record. The lines thus drawn were extended, without considering trajectory, through the dome.

caused by mud from the river bottom, since the products of combustion of Torpex are not dark-colored.

The plumes outside the spray dome have a velocity of about 120 feet per second. If these plumes are traced back into the dome to find the time and position of their origin, it seems probable that they started at about the time the gas globe collapsed, 1.36 second after the initiation of the explosion.

The point of origin of these plumes is indeterminate. However, in Figure 13 an attempt is made to trace it, based on the following reasoning. Since the velocity of the plume is known to be 120 feet per second, and since its direction and time of motion outside the dome are also known, it is possible to extrapolate to the time of collapse of the gas globe. By this method it is found that the origin of the plume was at least 10 feet below the water surface.

It should be noted here that although the detonation and the gas globe collapse were separated in time by 1.36 second, and although two distinct shock waves were recorded on the oscillograph, there was only one "boom" audible to the observers on the barge.

MOTION OF A BUOY IN THE SPRAY DOME

The vertical movement of one of the mine cases used as buoys can be traced in the photographs in Figure 10, from 0.025 second to 1.95 second. It is possible that the distance between the buoy and a point directly above the charge may have been greater than the 17 feet measured on the photograph, because the buoy may have been closer to the camera than was the charge. It seems improbable that the buoy was thrown upward with greater velocity than the surrounding water, and therefore the maximum distance from charge to buoy, assuming the buoy to be moving on the outer edge of the dome, could not have been more than 57 feet. Then, since a buoy weighing 147 pounds at a horizontal distance of 17 to 57 feet from a point directly above the charge was thrown upward with an initial velocity of 50 feet per second, it follows that 5700 foot-pounds of energy remained with the buoy after it had broken from its mooring.

DIRECTION OF MOTION OF WATER IN THE SPRAY DOME

From the diagram of Figure 14, which is a scale drawing of the charge position and the bottom, with a shock wave in its initial position and its reflection from the surface superposed, it is apparent that if the resultant force due to reflection at the surface acts in line with the bisector of the angle θ between the incident wave and the reflected wave, *all* the particles of water to which velocity is imparted should move vertically upward, regardless of their position in the spray dome. This is verified by published data (5) and by unpublished records at the Taylor Model Basin.

If, furthermore, ordinates are erected in Figure 14 at the points of intersection of the incident shock wave and the reflected shock wave with the surface and if on these ordinates vectors are drawn in proportion to the sine of half the angle θ included between the two waves,* it will be observed that the corresponding curve is in fair agreement with the actual and theoretical initial velocity curves of Figure 11. This may mean that for any charge at any depth a rough plot of relative initial velocities may be obtained. Furthermore, the initial velocity is closely proportional to the energy involved.

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* It will be noted that the angle included between the water surface and the radius of the incident wave drawn to its point of intersection with the water surface is equal to half the angle θ included between the incident and reflected wave.

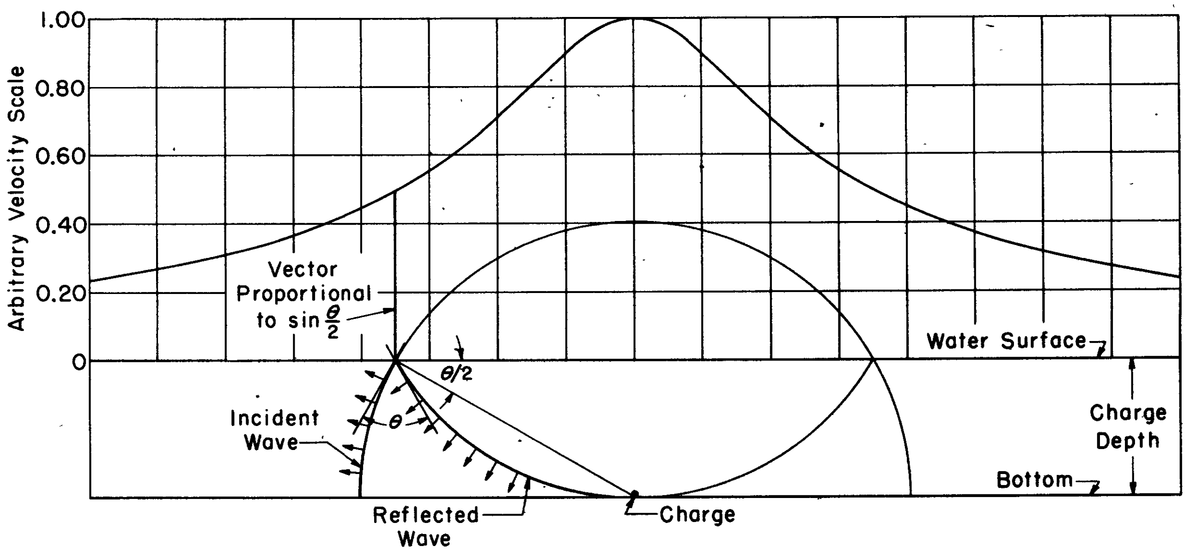

Figure 14 - Diagram Showing a Velocity Distribution Curve Obtained from a Geometrical Relationship Involving the Incident Shock Wave and the Water Surface

Velocity vectors proportional to the sine of half the angle included between the incident wave and the reflected wave are drawn vertical from the point of intersection of the shock waves with the water surface. The curve connecting the end of these vectors has a form very similar to those given in Figure 11.

It will be noted in Figure 11 and Figure 14 that the experimental curve falls off more rapidly than the theoretical curve of Kennard or the curve involving the relationship between the incident wave and the water surface. This is to be expected as frictional factors and surface tension will play an increasingly important role as the distance from the charge increases and the intensity of the shock wave decreases.

Here arises the interesting point of the actual amount of water in the spray dome. This is of interest not only as a measure of the amount of surface water that is peeled off and thrown into the air as large drops, but as a measure of the amount of water that is likely to fall upon a ship which is close to an underwater explosion. This water can short-circuit exposed electrical apparatus and run down ammunition hoists and ventilators; it may on the other hand be a blessing and extinguish an oil or gasoline or powder fire that has been started by the explosion.

Any consideration of what happens at and just under the original water surface must take account of the fact that there is an area of reduced pressure under the surface, behind the reflected wave, in which cavitation takes place. It is evident, therefore, that all the water that leaves the sea and flies into the air must have its full upward acceleration imparted to it *before* it becomes underlaid with a region of reduced pressure. This low pressure, acting with gravity, would immediately pull it back again.

CONCLUSIONS

Since the present test is the first of a projected series involving the underwater detonation of heavy charges of high explosive, definite conclusions as to the above-water effects of such explosions are as yet unwarranted. However, the results of this test seem to confirm those obtained with smaller charges.

During the preparation of the present report, tests were conducted with 1750 pounds of Torpex on the bottom in 100 feet of water. Results of these tests will be reported in the near future.

REFERENCES

(1) "Experiments on the Pressure Wave Thrown out by Submarine Explosions," by H.W. Hilliar, Department of Scientific Research and Experiment, CONFIDENTIAL Report R.E. 142/19, June 1919.

(2) "Notes on Some Double Dome Phenomenon with American Depth Bombs," by N.P. Rutherford, CONFIDENTIAL Report H/Arm/Res6, Undex 22, December 1942.

(3) "On the Time-Interval between an Underwater Explosion and the Appearance of the 'Plume'," Mine Design Department, CONFIDENTIAL Report SS1222, Undex 41, July 1943.

(4) "A Further Investigation into the Dome Analysis Method of Determining the Depth of Underwater Explosions," by R.A. Shaw, CONFIDENTIAL Report H/Arm/Res3, SW23, April 1942.

(5) "Surface Phenomena Following Underwater Explosions I, Some Preliminary Observations on High-Speed Motion Pictures," by J.E. Eldridge, NDRC, Division 8, Interim Report on Underwater Explosions and Explosives, March 15, 1944 to April 15, 1944.

(6) "Underwater Detonations - Static Plants of 500 Pound Bombs," by H.H. Moore, Naval Ordnance Laboratory, Experimental Ammunition Unit, EAU Report 731, July 1939.

(7) "Explosion Tests with 1750 Pounds of Torpex," by G.K. Hartmann, CONFIDENTIAL BuOrd Report Re2c, 29 March 1944.

(8) "Migration of Underwater Gas Globes Due to Gravity and Neighboring Surfaces," by E.H. Kennard, TMB CONFIDENTIAL Report R-182, December 1943.