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

A STUDY OF THE SURFACE EFFECTS CAUSED BY AN UNDERWATER EXPLOSION

PART 2

1750-POUND CHARGES OF TORPEX NEAR THE BOTTOM AND 40 FEET BELOW THE SURFACE, IN 96 FEET OF WATER

by

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PERSONNEL

These tests were 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. Ensign R.B. Baxter, USNR, of the Taylor Model Basin made the electronic pressure measurements and C.H. Bradley and C.W. Wyckoff took the motion pictures. The data were analyzed and the report was written by Lieutenant D.C. Campbell, USNR.

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ABSTRACT

Two charges of 1750 pounds of Torpex were fired, one close to the bottom and the other 40 feet below the water surface, in 96 feet of water. A time history of the dome and plume is given for each of these explosions as obtained from high-speed motion-picture records. An attempt at sound-ranging and correlation of pressure data with the dome and the plume is described.

INTRODUCTION

A study of surface effects produced by underwater explosions has been underway for some time in both the United Kingdom and the United States (1) (2) (3) (4) (5) (6) (7).* The present report is a continuation of the work described in Reference (8), in which data covering short time intervals were derived from ultra-high-speed motion-picture records taken at a rate of 1500 frames per second. The present report in conjunction with Reference (8) furnishes information concerning the effect of water depth and the influence of the bottom on large-scale explosions.

GENERAL FEATURES OF TEST

Two tests are described in this report. In the first, 1750 pounds of Torpex was fired just clear of the bottom in 96 feet of water, and in the second 1750 pounds of Torpex was fired at a depth of 40 feet in 96 feet of water. Both tests were conducted in Chesapeake Bay off Cove Point, about 4 1/2 miles from the mouth of the Patuxent River. Figure 1, copied from a U.S. Coast and Geodetic Survey map, shows the area of water in the vicinity and the soundings near the site.

The first test, in which the charge was fired near the bottom, occurred on 24 May 1944; due to poor weather conditions, however, no data were obtained. The test was repeated on 8 June and the results are contained in this report.

The second test in which the charge was fired 40 feet below the water surface was conducted on 10 June 1944.

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

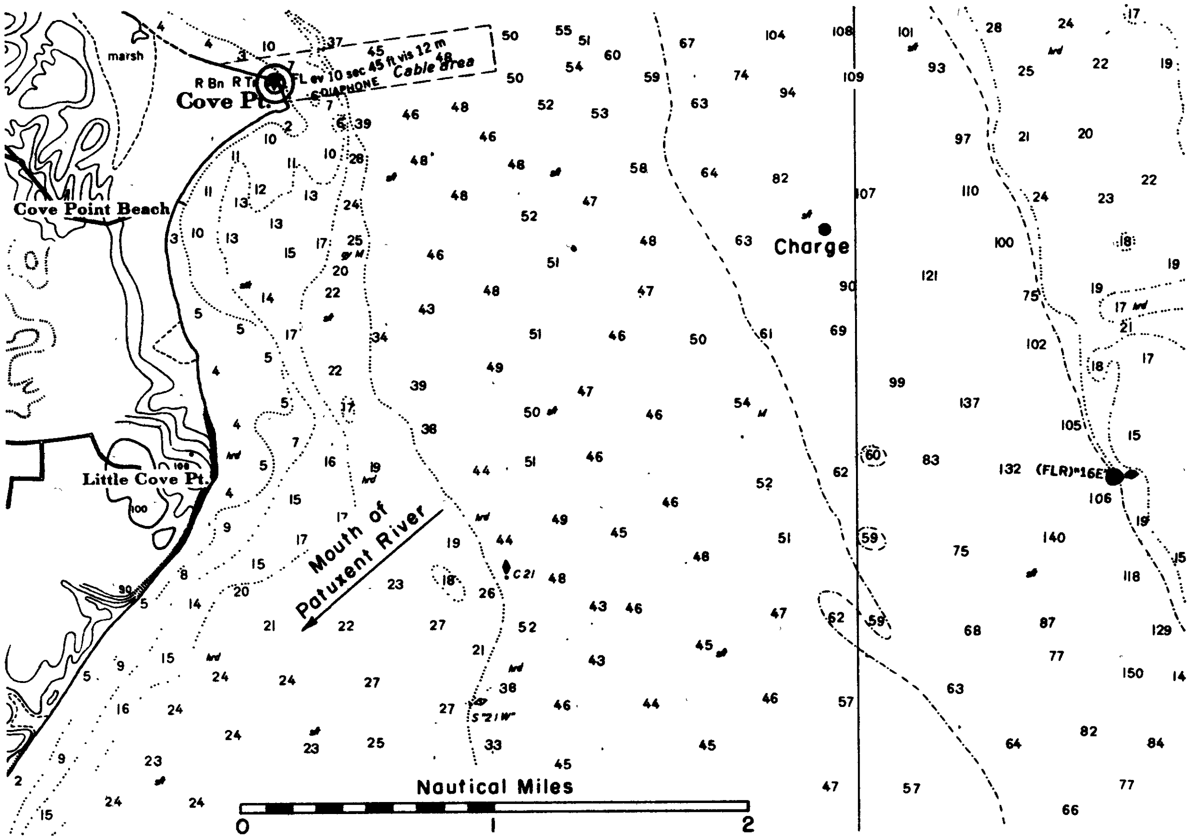

Figure 1 - Chart of the Vicinity of the Explosions in Chesapeake Bay

This figure was copied from the U.S. Coast and Geodetic Survey map of Chesapeake Bay from the Patuxent River to Sharps Island.

The charge and various mechanical pressure gages were suspended from telephone poles 80 feet long, as shown in Figure 2. The whole rig derived additional buoyancy from 8 empty mine cases about 32 inches in diameter lashed to the poles at a number of points along their length. The charge was suspended by a wire rope from the midlength of the poles. Two battens extending above the poles and marked off in 1-foot divisions were placed at the ends of the rig to provide a scale on the motion-picture records of the test. The distance between the battens was found to constitute a more reliable scale than the painted divisions. Figure 3 shows one of the test rigs being towed into firing position.

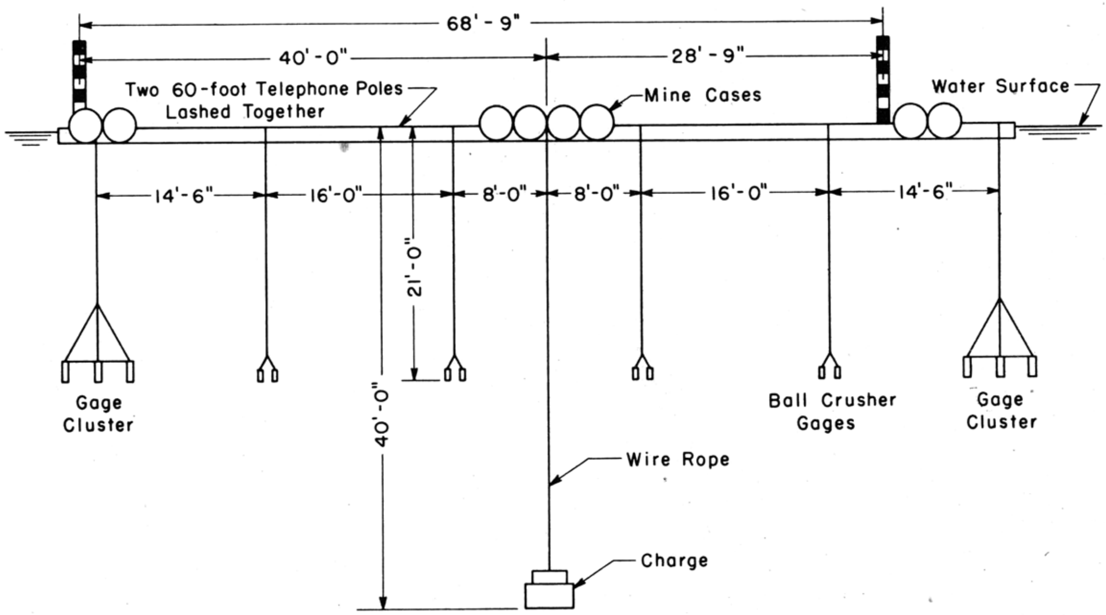

Figure 2 - Schematic Diagram of Test Rig for Supporting Charge and Gages

This diagram shows the rig as set up for the explosion of 1750 pounds of Torpex 40 feet below the surface in 96 feet of water. The wire rope supporting the charge was cut to place the bottom of the charge 40 feet below the water surface. However, the entire rig sagged in the center section so that the bottom of the charge was nearly 42 feet below the water surface. Eight mine cases lashed to the telephone poles were used for additional buoyancy. A large gage cluster was supported near each end of the pole, and ball-crusher gages were hung at other points along the length of the pole. Two battens, one at each end of the pole, were used for scales in the photographs. This rig is similar to that used with the charge fired near the bottom in 96 feet of water.

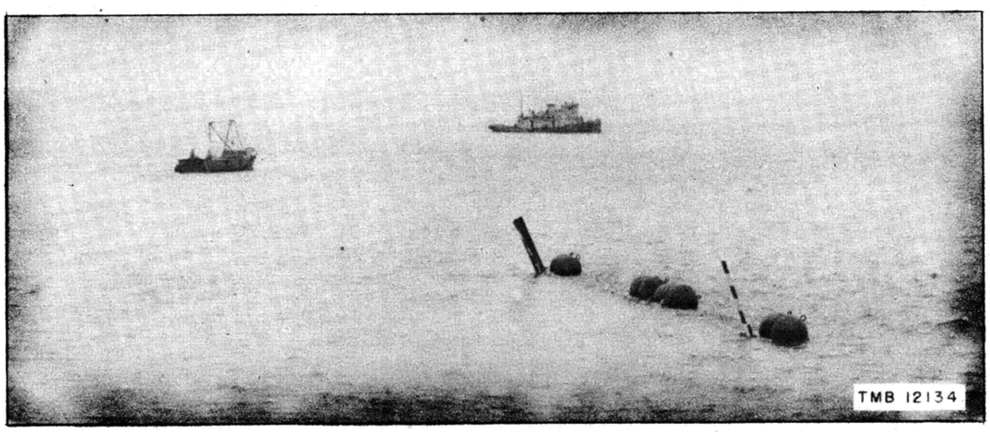

Figure 3 - Test Rig for Open-Water Explosions of 1750 Pounds of Torpex

Charge and gages are suspended from an 80-foot telephone pole buoyed up by 8 empty mine cases. To provide scales in the photograph, vertical battens were placed near the ends of the pole; these battens were painted with alternate black and white 1-foot squares. This photograph shows the rig being towed into position for the shot near the bottom in 96 feet of water. From center to center the battens were 68 feet 9 inches apart; the charge was suspended approximately at midlength of the poles.

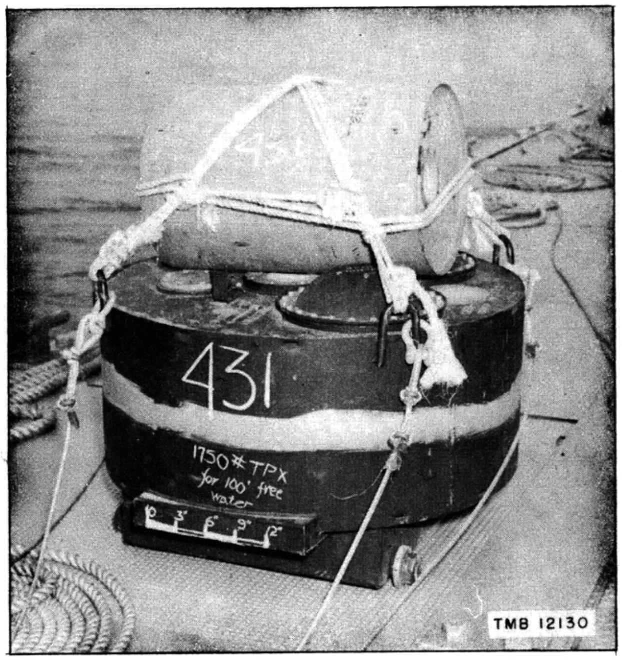

Figure 4 - Arrangement of the Charge of 1750 Pounds of Torpex

This is the charge used near the bottom in 96 feet of water and is identical with the charge fired at 40 feet in 96 feet of water. 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. The chalk scale at the bottom of the mine case will give a rough idea of the outer dimensions of the charge.

The charge which was fired near the bottom is shown in Figure 4. This is identical with the charge fired at a depth of 40 feet. A Mark 18 mine case was loaded with 1500 pounds of Torpex and a Mark 6 depth-charge case with 250 pounds of Torpex. Only half the volume of the depth-charge case was occupied by explosive, the remainder was filled with air. The detonator and booster were in the well of the depth charge and this unit was lashed to the top of the mine case. If only the upper charge exploded, the fact would be evident in the relatively small explosion.

TEST APPARATUS

Photographic, electronic-gage, and mechanical-gage records were made of various phenomena encountered in these tests. Figure 5 shows the positions of the barge and the small boat for each of the explosions. In both tests photographic records were made with one high-speed Jenkins camera and two Mitchell motion-picture cameras. One Mitchell camera and the Jenkins camera were mounted on a 6- by 18-pontoon Quonset barge; these cameras were operated by TMB personnel. The other Mitchell camera was mounted on an auxiliary boat, and was operated by personnel from the Naval Ordnance Laboratory. The TMB Mitchell camera ran at 24 frames per second and the NOL Mitchell camera ran at approximately 80 frames per second. The Jenkins camera ran at approximately 1600 frames per second.

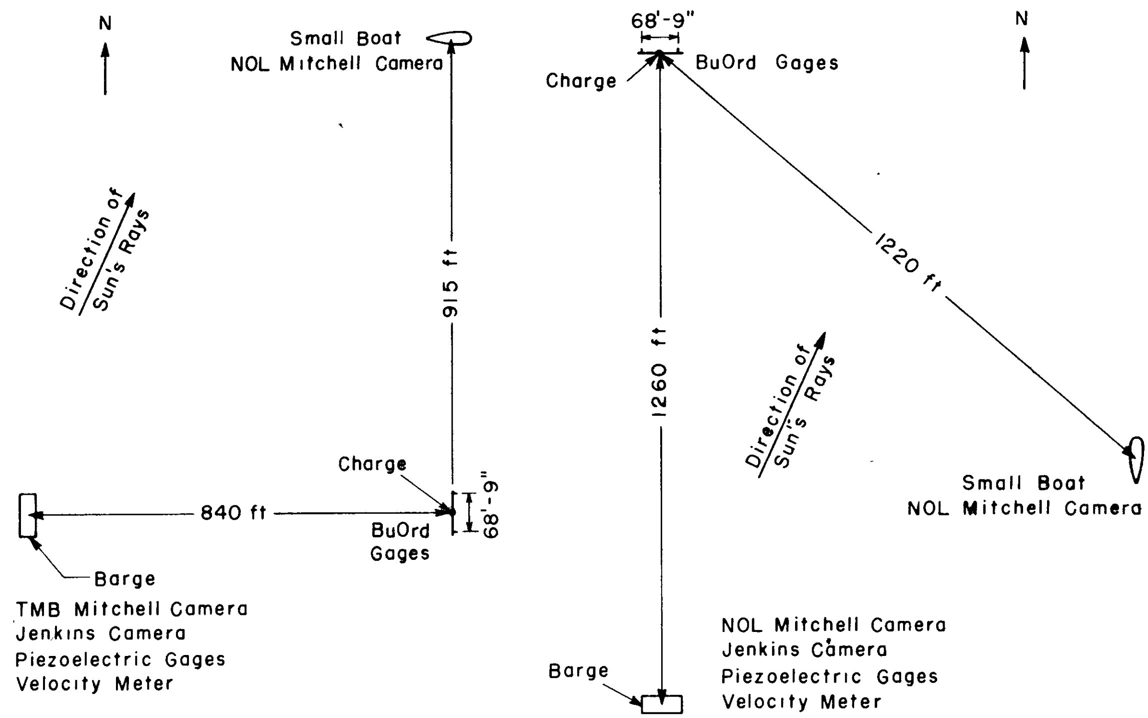

Figure 5a - Setup for the Explosion Near the Bottom

Figure 5b - Setup for the Explosion at 40 Feet

Figure 5 - Diagrams Showing the Positions of the Barge, the Small Boat, and the Charge for the Explosions of 1750 Pounds of Torpex

A direct-reading meter attached to the camera was used to indicate the frame frequency of the TMB Mitchell camera. The sweep hand of a split-second clock was photographed directly on the film of the NOL Mitchell camera and this was used to determine accurately the time between frames. A 100-cycle stroboscopic, high-voltage spark discharge was used to fog a small spot on the edge of the Jenkins-camera film. The same spark discharge was tied into the oscillographic equipment and was used for timing and correlation of the records.

The Bureau of Ordnance made an extensive series of mechanical-gage readings for each of the tests. Hilliar, momentum, and ball-crusher gages were used. Figure 6 is a photograph of one of the gage clusters used in one of the tests. A complete tabulation and discussion of the gage results and operations will be found elsewhere (9) (10).

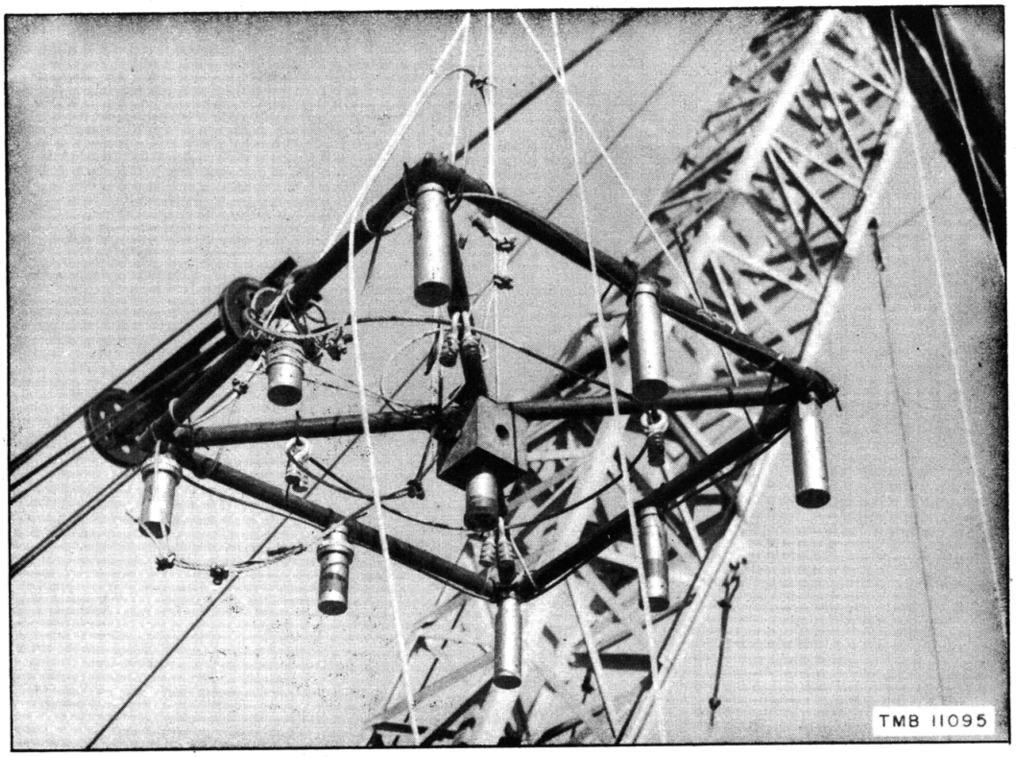

Figure 6 - Gage Clusters Used in Explosion Tests with 1750 Pounds of Torpex

Mechanical-gage readings were taken on all explosions by the Bureau of Ordnance. The cluster in this photograph has 1 Hilliar gage at the center and 8 momentum gages around the outside of the frame. Eight ball-crusher gages are suspended from the diagonals of the frame. A cluster of this type was hung at each end of the telephone poles supporting the charge.

For explosions of this type it is desirable, if possible to know the depth at which the gas globe collapsed at the first, second, and succeeding contractions. To accomplish this, a sound-ranging plan was devised which employed two piezoelectric pressure gages connected to a cathode-ray oscillograph. Although the British have been doing work of this kind for some time (11) (12), this is the first known attempt to sound-range in this manner in the United States. Since the time of the tests described in this report, the Underwater Explosives Research Laboratory, at Woods Hole, Massachusetts, has successfully employed sound-ranging in its investigations of explosives.

A graphical diagram of the temporary sound-range for the large Torpex shots is shown in Figure 7.

The sound-ranging attempted with these explosions employed piezoelectric pressure gages suspended at depths of 20 and 80 feet off the side of the barge about 1000 feet from the charge. The pressure pickups were fed into two cathode-ray oscillographs and both signals were recorded on a General Radio moving-film oscillograph recording camera. The film in the

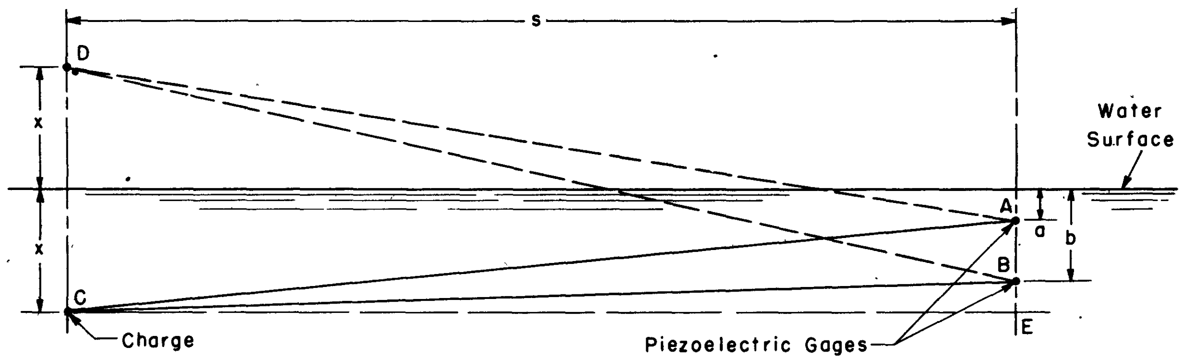

Figure 7 - Diagram of Sound-Range

A and B represent gages, and C is the source of the pressure pulse. The depths a and b of the gages and the horizontal distance s from the charge C to the gages A and B are known. The gages A and B will pick up a pressure pulse from C at different times. This difference ΔT is obtained from cathode-ray oscillograph records. It is readily seen from the geometry of the setup that the only unknown is the depth x of the source C, provided it is assumed that the gages A and B hang vertically above the point E.

recording camera ran for approximately 3 seconds at an average speed of 400 inches per second. The minimum time resolution was about 25 microseconds, giving an accuracy of plus or minus 2 feet in the determination of x.

The horizontal distance s was obtained by an optical range finder which was accurate to 6 feet. Computations are based on the assumption that the gages hang vertically in the water. The gages were lashed to a wire rope with an 80-pound weight attached to its lower end. Observation at the water surface indicated that the supporting cable assumed an angle off the vertical as a result of water currents. If computations involving the reflections from the water surface are used, any error introduced by the fact that the gages are not vertical will be eliminated.

Readings from a piezoelectric pressure gage hanging to a depth of 50 feet and from a velocity meter welded to the test barges were recorded on a Westinghouse string oscillograph. The velocity meter was a Sperry vibration pickup and was oriented to record horizontal velocity of the barge on a line through the charge.

TEST PROCEDURE

With the auxiliary boat at a distance from the test barge, communications became difficult. Shortwave radio was tried but was found to be of little use since the available radios were continually out of service. A Very pistol was used to signal 1 minute and 10 seconds prior to the firing of the charge. At 10 seconds the TMB Mitchell camera and the Westinghouse string oscillograph were started. At 6 seconds the NOL Mitchell camera was started. At 1 1/2 second the Jenkins camera was started. The General Radio cathode-ray oscillograph recorder was started at 1/2 second, and the charge was fired at zero time. All switches were closed manually.

TEST RESULTS

The above-water action observed in these tests occurred, as would be expected, in two distinct phases: the spray dome, and the plume. Enlarged frames from the TMB Mitchell record are shown in Figure 8 for the charge near the bottom in 96 feet of water, and in Figure 9 for the charge fired at a depth of 40 feet in 96 feet of water. This record was not analyzed but the photographs are illustrative and are better suited for reproduction than the Jenkins-camera record from which the analysis was made.

The extent of the above-water action and the records of the Bureau of Ordnance gages indicate that both parts of the charges detonated completely (10).

The shot near the bottom produced a dome having a greater diameter but less elevation than the 40-foot shot. The earliest frame indicated an area of discolored water 210 feet in diameter. This was less than 0.02 second after detonation and less than 0.001 second after the start of the surface disturbance. This dome rose to a height of 50 feet and its base attained a diameter greater than 400 feet, all in 1.20 second. The top of the spray dome remained approximately at this height for 0.75 second while the base diameter decreased to about 300 feet. At 1.96 second a plume, shooting nearly vertically upward, appeared at the top center boundary of the spray dome. This plume, 40 feet in diameter, rose 112 feet in the air in about 2.5 seconds. The sides of the plume appeared smooth which gave it the appearance of a giant monolith. Secondary plumes appeared moving upward around the base of the major plume at approximately 2.5 seconds.

For the 40-foot shot the visible spray dome was 120 feet in diameter in the earliest Jenkins-camera record obtained. This is less than 0.01 second after detonation and less than 0.001 second after the start of the surface disturbance. The dome rose to 110 feet in 1 second and reached a maximum height of more than 200 feet in 2.5 seconds. Plumes appeared through the edge of the spray dome at 1.92 second, traveling with an initial velocity of 160 feet per second on an angle of elevation of approximately 45 degrees.

In both shots a dark band was observed on the water surface outside the spray dome. This dark band had an outer diameter at least 50 per cent greater than the diameter of the spray dome.

The oscillograms of pressure and velocity give good records of the initial shock wave. Following the shock wave there was no evidence of a globe collapse or of any other phenomena on either shot. This is not understood in the light of Figure 7 of Reference (8), especially as there was every indication that the gages and electronic apparatus were functioning properly in all tests. It is possible that the second pulse in Figure 7 of Reference (8) is spurious. The shock wave reflected from the water surface arrives at the pressure gage a short time after the direct wave and tends to immediately cancel the direct wave. This canceling effect may have occurred and, owing to thermal gradients or some other unknown phenomena, the reflected and direct waves may have reached the gages with time separations less than could be resolved on the film. The bottom and its influence on wave reflection is also unknown.

It should be noted here that only one "boom" was audible to observers on the barge.

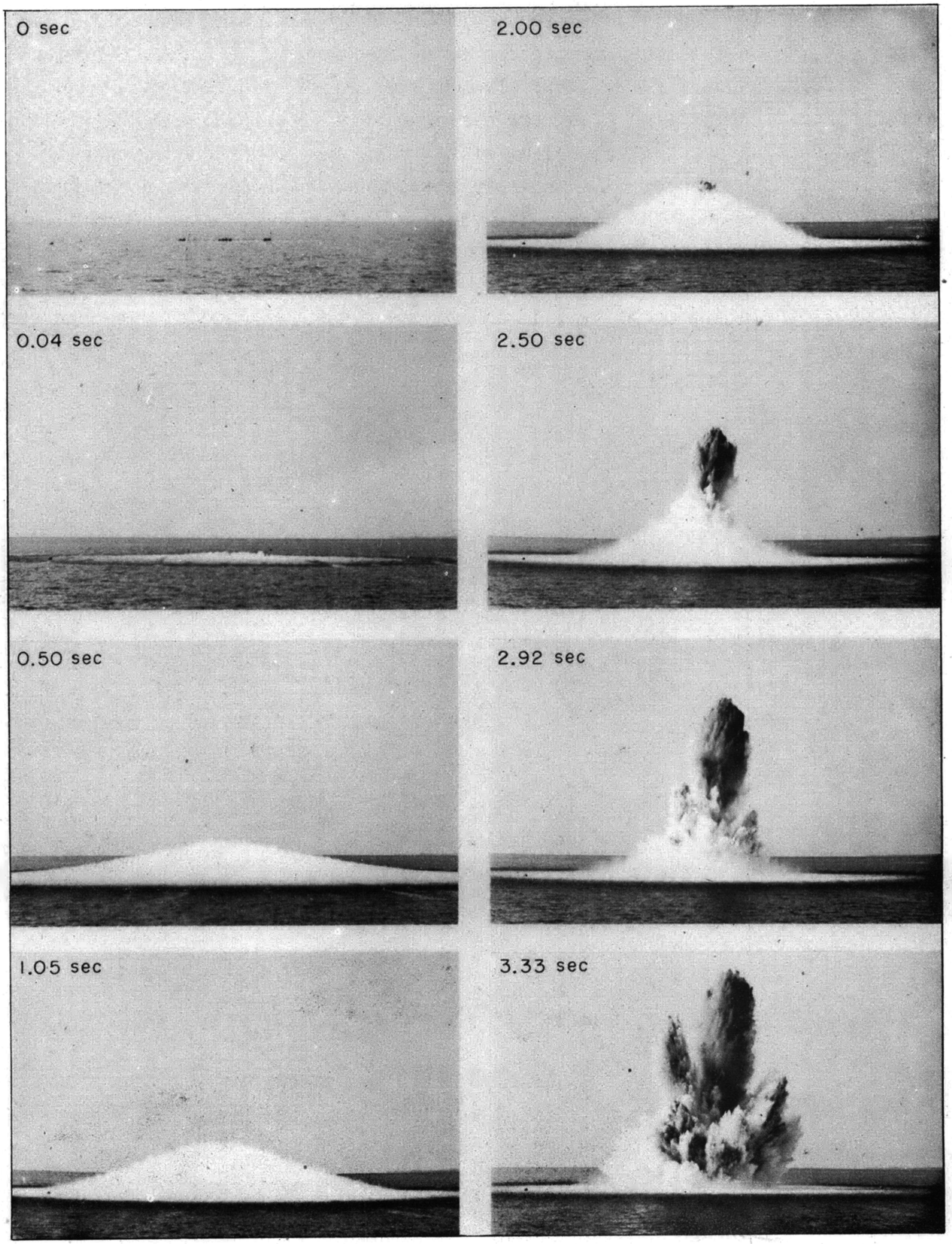

Figure 8 - Growth of Spray Dome and Plume from the Explosion of a 1750-Pound Charge of Torpex Fired near the Bottom in 96 Feet of Water

Practically the only change in appearance of the dome between 1.05 second and 2.00 seconds was the emergence of the plume near the crest of the dome.

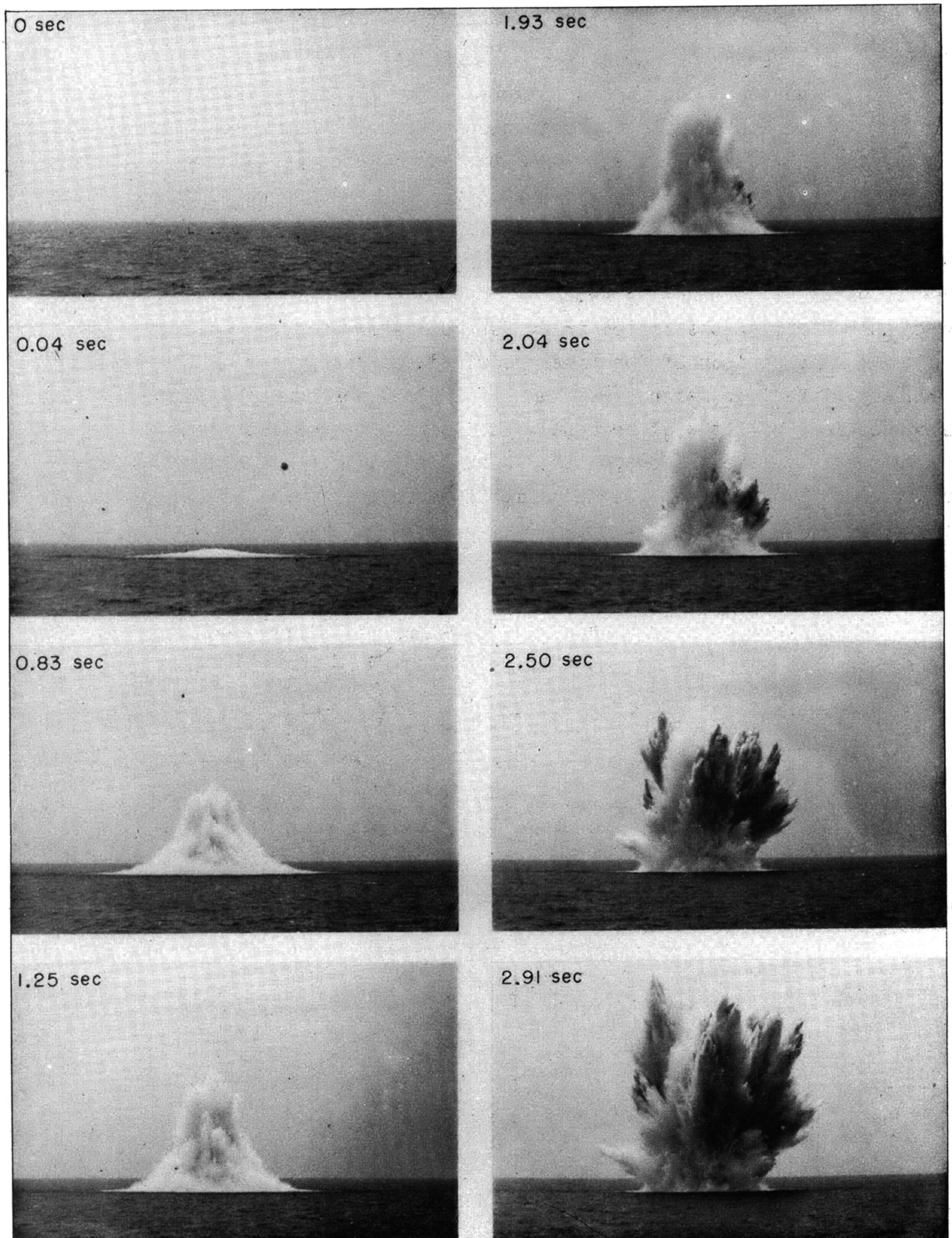

Figure 9 - Growth of Spray Dome and Plume from the Explosion of a 1750-Pound Charge of Torpex Fired at a Depth of 40 Feet in 96 Feet of Water

ANALYSIS OF RESULTS

A time history of the spray dome and plume was obtained from the Jenkins-camera record. These data are plotted in Figure 10 for the shot on the bottom in 96 feet of water and in Figure 11 for the shot at a 40-foot depth.

A fairly accurate determination of the rate of rise of the uppermost boundary of the dome is possible from the short intervals between exposures on the Jenkins camera. The maximum initial velocity, directly over the charge, was 162 feet per second for the 40-foot shot and 72 feet per second for the 96-foot shot. The upward velocity of the spray dome in the 40-foot shot in 96 feet of water is in exact agreement with that of the 1750-pound Torpex shot previously fired on the bottom in 40 feet of water (8).

A comparison of the times required for the center of the dome to reach any of various heights is given in Table 1 for three shots with 1750 pounds of Torpex. It will be noted that there is excellent agreement between the two shots at the 40-foot depth. Furthermore, in equal times the domes from the shots at 40 feet reached slightly more than twice the height of the dome from the 96-foot shot.

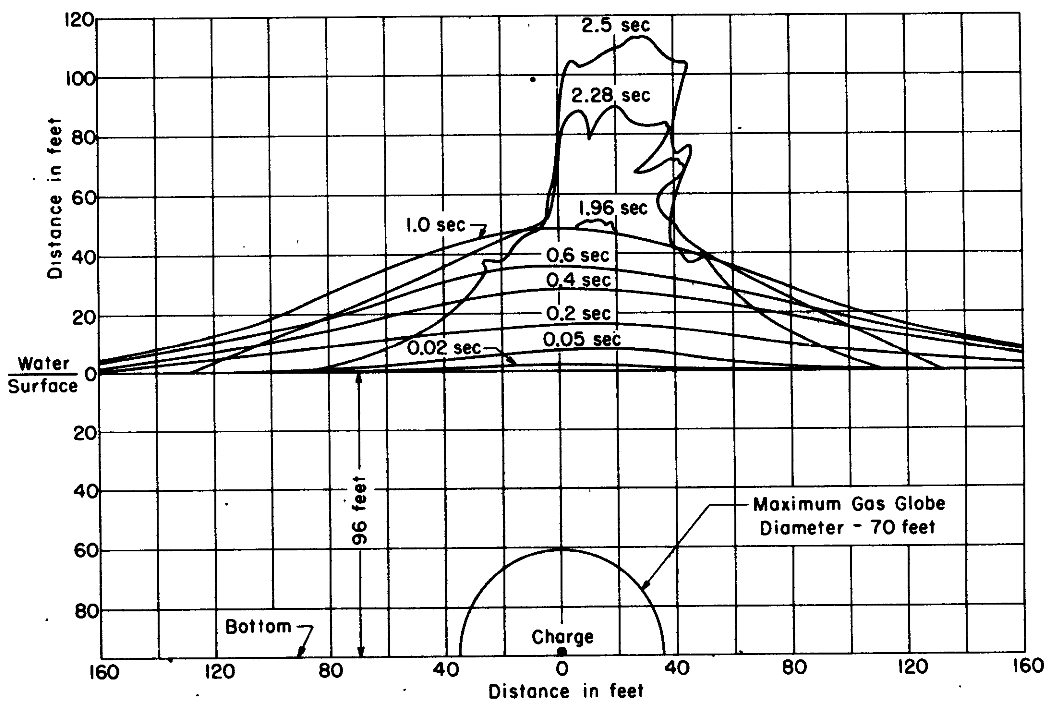

Figure 10 - Time History of Dome and Plume from the Explosion of 1750 Pounds of Torpex near the Bottom in 96 Feet of Water

Neglecting bottom effects, at a depth of 96 feet a charge of this size would theoretically produce a gas globe with a maximum diameter of about 70 feet in approximately 0.46 second (13) (14).

These curves were drawn from measurements made on the Jenkins-camera record.

TABLE 1

Comparison of Above-Water Heights for Various Underwater Explosions of 1750 Pounds of Torpex

The data given in this table were taken from Jenkins-camera records.

Time in seconds	Height of Rise in feet			Time in seconds	Height of Rise in feet		
	Shot at 40 feet in 96 feet	Shot on the Bottom in 96 feet	Shot on the Bottom in 40 feet		Shot at 40 feet in 96 feet	Shot on the Bottom in 96 feet	Shot on the Bottom in 40 feet
0.03			10	0.48			70
0.04			20	0.57	70		
0.05	10			0.62			80
0.09		10		0.68	80		
0.12	20		30	0.72			90
0.17	30			0.76	88	40	93
0.25	40	20	40	0.80	90		
0.34			50	0.86			100
0.35	50			0.89	100		
0.42			60	0.97			110
0.46	60	30	67	1.01	110		
				1.23		50	

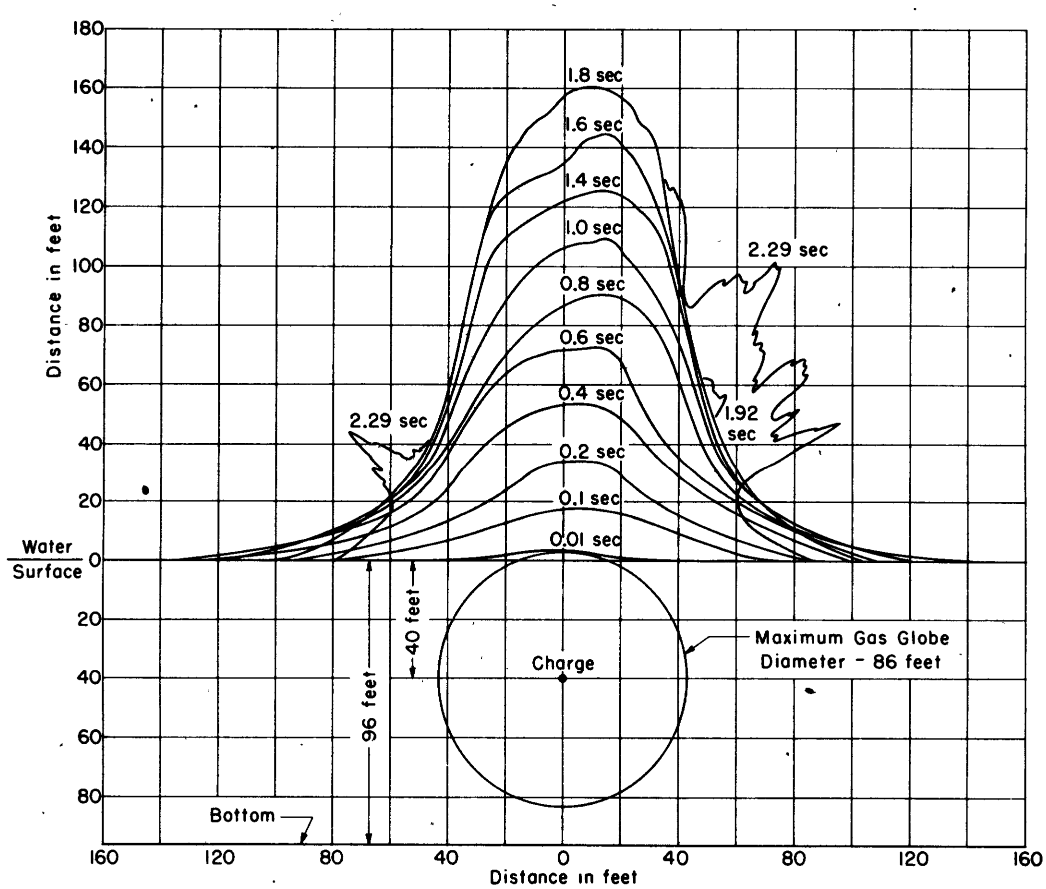

Figure 11 - Time History of Dome and Plume from the Explosion of 1750 Pounds of Torpex at a 40-Foot Depth in 96 Feet of Water

A charge of this size would theoretically produce a gas globe with a maximum diameter of about 86 feet in approximately 0.75 second (13) (14).

These curves were drawn from measurements made on the Jenkins-camera record.

Figure 12 has been drawn the better to visualize the dome phenomena resulting from shots at two different depths. The depth ratio D_1/D_2 is 2.4, which would correspond to depths of 96 feet and 40 feet. Two sets of curves have been drawn connecting the ends of vertical vectors drawn from various points along the water-surface abscissa.

One set of curves are drawn inversely proportional to the distance R from the charge to the water surface and directly proportional to the sine of the angle θ which the normal to the shock wave makes with the water surface. These curves, shown as broken lines in Figure 12, should give an approximation of the velocity distribution along the water surface.

The second set of curves, shown as solid lines in Figure 12, are drawn with vectors proportional to $(1/R^2)$ sin θ, which is representative of the energy distribution along the water surface.

A third set of curves, shown as dotted lines in Figure 12, give the actual initial velocity distribution as obtained from the Jenkins-camera record. The observed and the theoretical curves of velocity are in fair agreement directly above the charge but the curves of observed velocity fall off at a greater rate than the theoretical curves as the distances from the charge increase. The maximum observed velocity v_2 for the 40-foot shot was 162 feet per second. The maximum observed velocity v_1 for the 96-foot shot was 72 feet per second. The ratio v_2/v_1 is 2.25. The theoretical ratio of the initial velocities V_2/V_1 is 2.4. This discrepancy in the ratio was not expected since greater losses would be expected from the 96-foot depth which should produce a velocity ratio greater than 2.4, rather than less.

It is to be noted that both the energy and velocity curves cross at some definite distance from a position directly over the charge. This explains the larger dome diameter on the 96-foot shot and should be of importance in statistically determining the best spacing for mine laying.

Contrary to the previous belief (8) (9) that the products of the explosion of Torpex are not dark-colored, an investigation of the water surface over the charge position after the explosion showed large quantities of black carbon froth. Therefore the plumes, streaked with black, in contrast to the white spray dome, are not necessarily discolored by mud from the bottom. Examination of photographic records of the shot at 40 feet in 96 feet of water, Figure 9, show these dark plumes under a condition where the gas globe is assumed not to come into contact with the bottom.

It will be observed in the pictures of Figures 8 and 9 that the spray dome appears as a white mass of water. This is due to the water surface being thrown up into many fine drops that reflect light. The dark band outside the spray dome may result from a fine wave pattern on the water surface,

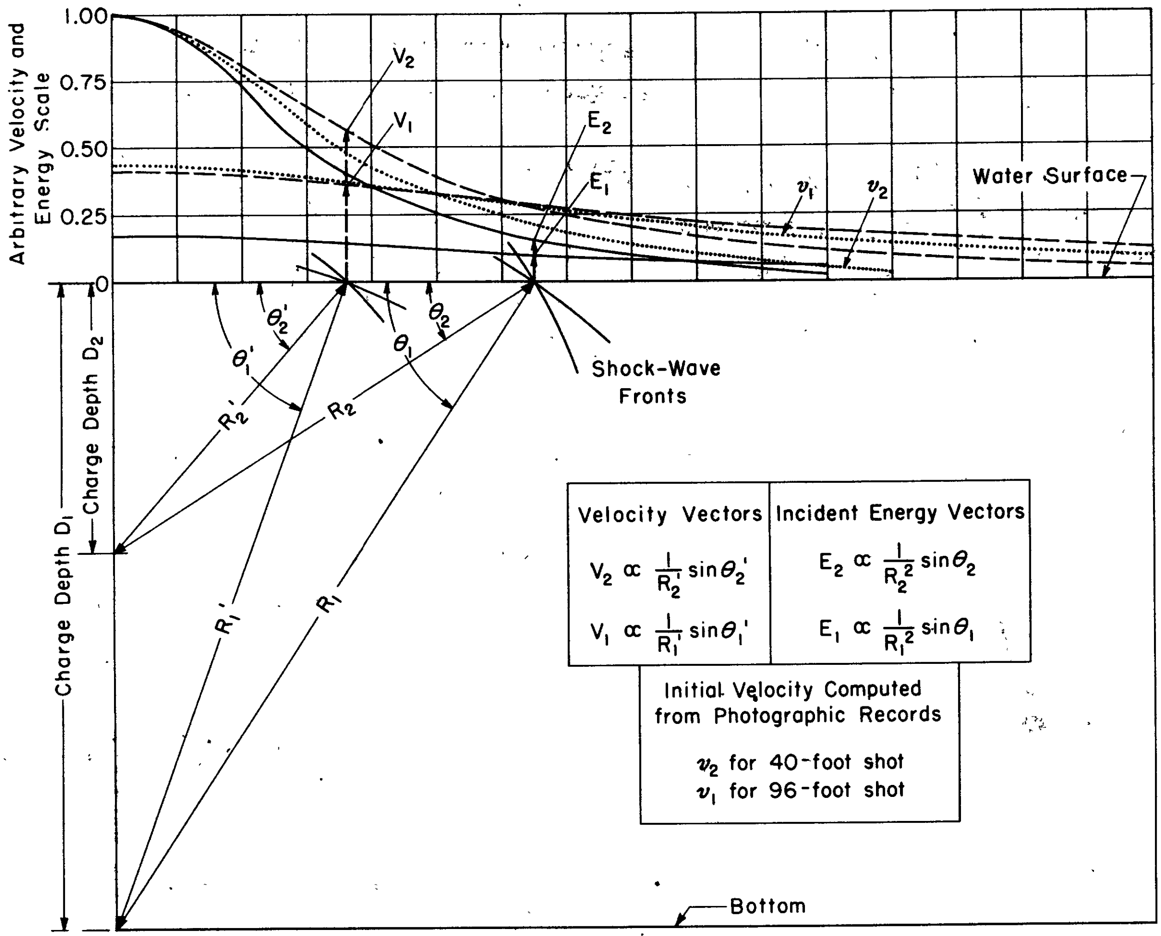

Figure 12 - Diagram Showing Relative Velocity- and Energy-Distribution Curves Obtained from the Geometry of the Charge Positions

Velocity vectors V_1 and V_2 proportional to the sine of the angle θ which the normal to the shock wave makes with the water surface and inversely proportional to the shock-wave radius R, are drawn vertically from the point of intersection of the shock wave with the water surface. Curves of the observed initial velocity v_1 and v_2 of the water surface, resulting from the explosion of 1750 pounds of Torpex at depths of 40 feet and 96 feet, are given.

Approximate incident-energy vectors, E_1 and E_2, proportional to the sine of the angle θ which the normal to the shock wave makes with the water surface and inversely proportional to the square of the shock-wave radius R, are drawn vertically from the point of intersection of the shock wave and the water surface.

The subscript 1 indicates variables for the 96-foot depth; the subscript 2 indicates variables for the 40-foot depth.

which disrupts the light reflections ordinarily picked up by the camera. A similar but much smaller effect is observed to result from the waves produced by surface wind in the foreground of the pictures.

CONCLUSIONS

An inspection of Figure 10 in Reference (8) and of Figures 10 and 11 in the present report, together with a careful study of these photographs, reveals that the spray dome and the plume phenomena are distinctly different, even more so than the shock-front and the gas-globe phenomena which produce them.

As previously pointed out (1) (8) the spray-dome motion is invariably vertical while that of the plumes is predominantly radial, from some center or source as yet undetermined. These streams of water particles cross each other on the inside of the above-water disturbance.

As is to be expected, the spray-dome phenomena are directly related to the depth at which an explosion takes place. For the same weight of charge the initial vertical water velocity at any point on the water surface is approximately proportional to the inverse first power of the distance from the charge to that point, and the sine of the angle between the water surface and the line from the surface to the charge.

The presence of the bottom appears to have no noticable influence on the above-water action. The bottom here is soft and probably yields for some depth and distance in a manner much the same as water. It would be interesting to examine similar explosions on rigid rock bottoms. However, in practice most underwater explosions with which we are concerned will take place over bottoms of mud, silt, and similar soft material.

Other tests have been conducted with high-speed photographic recording and their results will be reported in the future to add to the general knowledge of underwater explosion phenomena.

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