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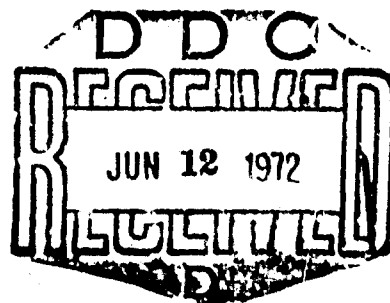
A Two-Camera System To Study Underwater Explosions

by

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and

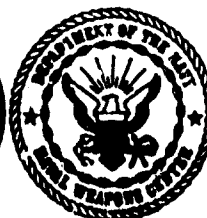
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ABSTRACT

A photographic system is described which uses two high-speed framing cameras, special illumination techniques, and appropriate synchronization to study the behavior of small underwater explosions in both the microsecond and millisecond time ranges. A Cordin camera is used to study pressure pulse behavior and the formation of cavitation fields. A Fastax camera is used to study the bubble effect and gross water motion. Typical results obtained from such a two-camera system are discussed in terms of one specific test.

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W. I. Moran, RADM, USN Commander
H. G. Wilson Technical Director

FOREWORD

This report represents part of a continuing program conducted by the Detonation Physics Division, Research Department, to study small underwater explosions and resulting target response in terms of the various phenomena which occur in both the microsecond and millisecond time ranges. The studies were performed during fiscal year 1972 and were funded by Airtask ZR00001 2303.

The information is released at the working level and is subject to modification.

Released by
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Research Department
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INTRODUCTION

A photographic system which uses two high-speed framing cameras, special illumination techniques, and appropriate synchronization, has been devised to study in detail the various behavioral aspects of small underwater explosions. The explosive charges are detonated in a water-filled tank having either glass or lucite sides to allow for external viewing of the explosion phenomena. Separate and independent lighting schemes using both sunlight and an electronic flash unit are employed to illuminate the events, with the light sources and cameras located external to the tank.

The system uses two types of high-speed framing cameras operating at different framing rates in order to study those phenomena which occur in both the microsecond and millisecond time ranges. A Cordin camera operating at about 100,000 frames per second is used to view pressure pulse propagation, reflections, and interactions; and the formation of cavitation fields. A Fastax camera operating at 1,500 to 3,000 frames per second is used to view the same explosion in terms of bubble oscillations, migrations, and interactions; and the gross effect of water motion on underwater objects.

These photographic studies were initiated to investigate the phenomena associated with small underwater explosions and their effect on underwater metal-forming operations. Of particular interest are the interactions between low-density regions in the water (i.e., cavitation fields, cavitation tunnels, and bubble curtains) and explosion-induced effects such as the primary pressure pulse, bubble oscillations, and water motion. By studying and understanding such interactions it is hoped that they can be utilized more effectively in underwater operations.

The controlling variables in most underwater standoff operations are mainly the charge size and the standoff distance. Different charge size and standoff combinations can be used to produce long standoff or short standoff effects. For a long standoff operation, the workpiece response is based almost entirely on the action of the primary pressure pulse. Under such conditions of loading, the quantitative nature of the load parameters can be established from known free-water relations (Ref. 1-4). For short standoff operations the bubble effect can become an important contributor to the loading process, so that superimposed on the action of the pressure pulse are additional load effects which may result when (1) the explosion gases in the bubble are applied directly against the target, and (2) work is obtained from the kinetic energy of the gross water motion. The quantitative nature of the bubble loading is more

difficult to establish than that for the pressure pulse, and the interrelation between bubble behavior and target response is currently one of the more important areas in underwater forming in need of detailed study.

The present two-camera system allows the investigator to study the microsecond and millisecond behavior patterns separately for a single explosion. In this way, details of the system response, first to the pressure pulse, and then to the bubble effect, can be separated into meaningful areas of study rather than being masked by the composite, over-all loading. This report describes the two-camera system currently being used, and discusses the types of results which can be obtained in terms of one specific test involving a detonator and several underwater objects. The events which occurred in both the microsecond and millisecond time ranges for this test are reviewed in some detail.

DETAILS OF THE TWO-CAMERA SYSTEM

GENERAL

A number of tests were conducted to establish the design needs of the tank and the photographic requirements of the overall system in order to study small underwater explosions. The basic experimental arrangement which was developed is shown in the plan view sketch of Fig. 1. It consists of a water-filled tank, two high-speed framing cameras, light sources, and a fresnel lens. The tank is made with glass or lucite sides and contains the explosive charge and any other objects such as targets, bubble curtains, cavitation fields, pressure pulse reflectors, and the like which may be required for any given test. A Cordin camera was selected to view the fine details of pressure pulse behavior, the formation of cavitation fields, and similar phenomena which occur in the microsecond time range. After considerable experimentation, it was decided that the topics to be covered by the Cordin camera could best be viewed by a shadowgraphy technique in which the backlighting was accomplished by means of a fresnel lens and a modified flash unit. A full-frame 16 mm Fastax camera was chosen to monitor the gross behavior of the explosion including the bubble oscillations and migration, and the response of underwater targets, all of which take place in the millisecond time range. Lighting for the Fastax camera was provided by direct sunlight, or sunlight and reflectors. The relative location of the major components of the two-camera system for an actual test are shown in Fig. 2. The Cordin camera is not visible since it is inside the barricade in the background

WATER TANK DESIGN

Based on the requirements of the experimental program, the water tank had to be capable of taking the shock loading from the detonation of from one to three detonators, with the multiple charges fired either

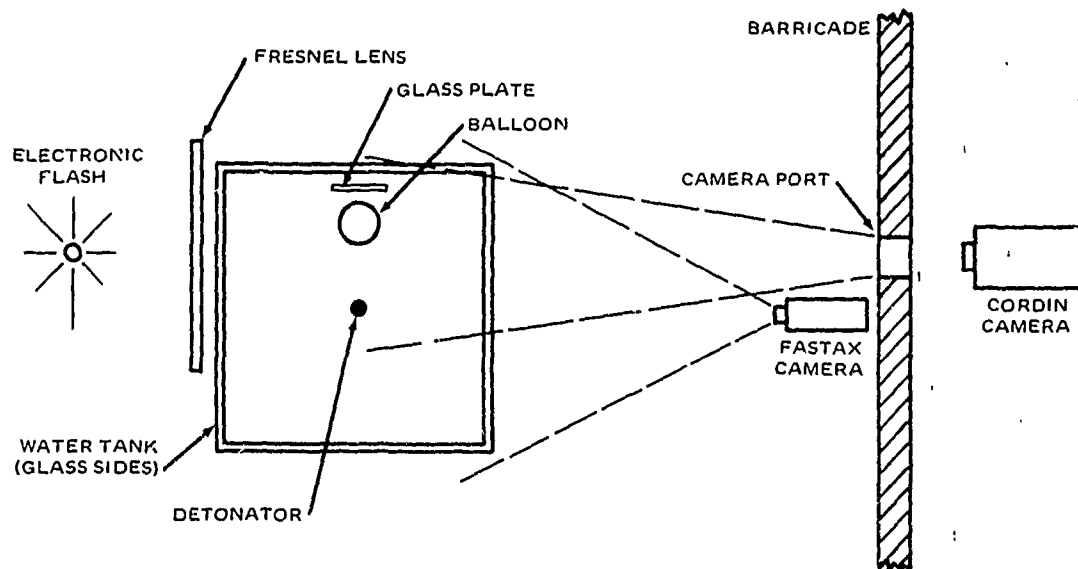


FIG. 1. Plan View of Two-Camera System.



FIG. 2. Experimental Setup for Two-Camera System.

simultaneously or with some predetermined delay times. This represented a total base charge of up to 12 grains of RDX and 9 grains of lead azide or similar amounts of other comparable explosives. Also, the tank had to be capable of withstanding the effect of focussed loads which might result from the use of pulse reflectors.

The first experimental tank was constructed of four glass plates sealed at the corners to form the sides of the tank, and then sealed to a steel bottom plate. The outside dimensions were 30 inches wide by 30 inches long by 30 inches deep. The sides were made of 3/4-inch-thick double-layer laminated glass, with each piece composed of two 3/8-inch-thick layers bonded together with cellulose acetate. The four sides were reinforced by upper and lower sets of steel bands with tightening bolts, and were fastened to the steel base by adjustable rods. This tank was excellent for tests involving just the detonators. However, the glass would break whenever bubble energy was purposely directed to one of the sides. After replacing the glass sides with 1-inch-thick lucite plates, the tank was quite satisfactory.

A second experimental tank was built in order to increase the field of study for some of the tests (Fig. 2 and 3). The outside dimensions of this larger tank were 49 inches wide by 50 inches long by 38 inches deep. This one was constructed with an angle-iron frame using 3/8-inch steel angle with 6-inch legs. The tank had 1 1/2-inch-thick lucite walls and a 1-inch-thick steel bottom. The frame and bottom were of welded construction with the lucite sides sealed in place. A 2-inch valve was placed in the bottom of the tank for draining the water.

CORDIN CAMERA SYSTEM

The Cordin camera is a high-speed framing camera which provides 25 frames of viewing on 35 mm film, and has a preset framing rate in the general range of about 10,000 to 5,000,000 frames per second. The exposure time for each frame is determined by the rotational sweep rate of a high-speed rotating mirror, and the interdiction of the light rays by a fixed optical shutter which involves two apertures or gates. The Cordin camera was used for viewing those aspects of the explosion related to the pressure pulse and the formation of small cavitation fields.

Determination of the appropriate framing rate was based on the nature of the event and the required time of coverage. Since the underwater pressure pulse is traveling at a velocity of about 4,800 feet per second, and the propagation distance for the primary pulse and reflections in the experimental field might be expected to total about 20 inches, this would indicate a total event time of approximately 350 microseconds. This period could be adequately covered with a framing rate of 66,000 frames per second, with an interframe time of 15 microseconds.

Initial studies with the Cordin camera indicated that for a single detonator located 3 to 4 inches from a membrane surface, cavitation

started almost instantaneously upon impingement of the pressure pulse (i.e., within several microseconds), and the cavitation field had a duration of about 1 millisecond or somewhat longer. Thus, a framing rate of about 25,000 frames per second, with an interframe time of 40 microseconds, would be required to cover the history of the cavitation field, while the above faster value would give a more detailed coverage of its initial formation.

From the manner in which the camera is constructed there is a fixed ratio between the exposure time for each frame and the interframe time. In the present studies the exposure time for each frame was considered to be approximately one-third the interframe time. In order to establish satisfactory coverage of an event in the microsecond range, it is necessary to consider both the duration time of the event for complete coverage, and the exposure time relative to the motion of the event for sharpness of image. The established framing rate usually becomes a compromise between these two considerations.

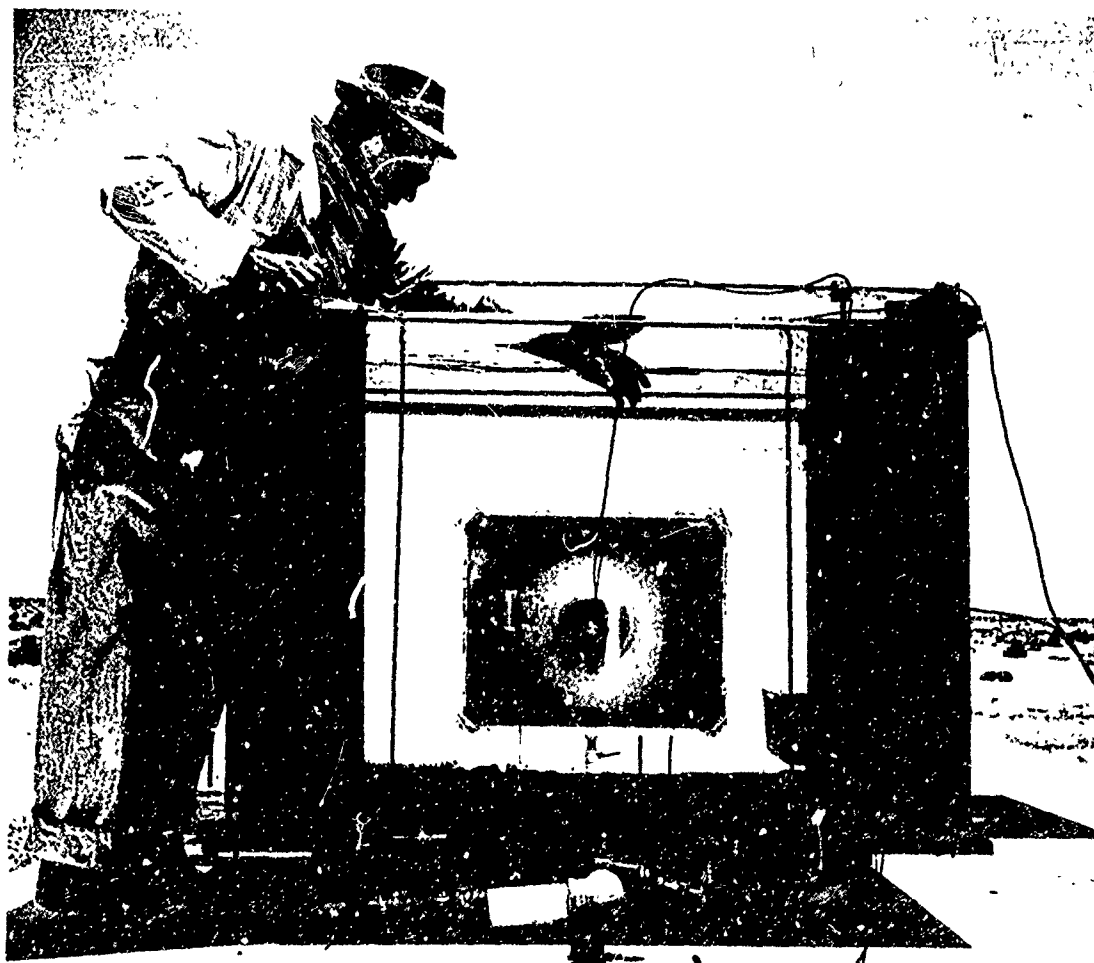


FIG. 3. Water Tank With Fresnel Lens on Far Side.

A number of tests were conducted with the Cordin camera using different framing rates with interframe times such as 15, 10, and 6 microseconds, with the major emphasis being coverage of the pressure pulse. In general, for an interframe time of 15 microseconds (66,000 frames per second) the exposure time for each frame was somewhat too long, so that the image of the pulse front was blurred more than was desired. Interframe times of 10 and 6 microseconds (100,000 and 166,000 frames per second) both gave a satisfactory image and were used for experimental studies. For some tests the 6-microsecond interframe rate gave a total duration which was too short to adequately cover the pulse behavior in the experimental field of view. For these latter studies, the 10-microsecond interframe rate was a satisfactory compromise. The film used in the Cordin camera was High-Speed Ektachrome with a film speed of ASA 160 with normal processing.

LIGHTING FOR THE CORDIN CAMERA

A focussing shadowgraph technique was used to best illuminate the pressure pulse and the reflected waves resulting from the detonation. The subject was placed between the Cordin camera and a Fresnel lens with backlighting to illuminate the water and make the shock waves visible by refraction. The camera view of the water tank with a Fresnel lens on the far side is shown in Fig. 3.

The light for the background lens was a Beckman and Whitley (Cordin) Mod 357 electronic flash unit, which is made to give a level peak, long duration flash. The light was modified to receive a quenching pulse from the Cordin camera delay synchronizer. This limited the light pulse to a duration slightly longer than the camera recording time, and prevented multiple exposures on successive camera mirror sweeps over the film. The end of the helical coil flash tube was capped with an aperture of 0.75-inch diameter to adequately fill the area of the Fresnel lens with background light. The aperture was covered with a translucent diffuser so that the flash tube light emitted as a source at the aperture plane.

In a focussing shadowgraph system the light, after passing through the Fresnel lens, is directed as a converging bundle through the subject plane and to a point of focus near the lens and primary shuttering aperture. Some rays are refracted away from their undisturbed path by passing through the pressure boundary of the shock wave. If the rays are bent out of the bundle entering the camera, there is a resultant darkness of the image along this boundary. Some rays can also be refracted onto adjacent areas already lighted from undisturbed rays. The result then is a boundary image lighter than the background.

Shock wave definition within the limits of the focussing shadowgraph technique can be further enhanced by utilizing diffraction effects (color fringes) that occur as a result of the Fresnel lens having no color correction. The edge of the source light disc reveals a color fringe when viewed from the film plane through the system. Recorded in

color, the image of the shock wave front will show as one color against another as well as light against dark. In order to utilize this color effect, all of the Cordin studies were conducted with High-Speed Ektachrome film.

The image of the edge of the source disc of light is near the outer edges of the Fresnel lens. Earlier tests had shown more sensitivity to shock waves in the outer area than near the center of the illuminated field where there was no light-dark boundary to help define refractive changes. To make the control area of the illuminated field more sensitive, a 0.25-inch-diameter opaque stop was set in the center of the light source. The source light was adjusted so that the blue component of the diffracted light passing the edge of the stop was imaged on the film. The sensitivity of the central area was in this way made more equal to that of the edges.

FASTAX CAMERA SYSTEM

A full-frame 16 mm Fastax camera was used to study those events which take place in the millisecond time range. These include the time-history of the bubble through several oscillations covering shape, migration, interaction with underwater objects, and venting; gross water motion; and target response. The bubble period for a detonator is roughly 20 milliseconds, and the total duration of the event to be covered by the Fastax is about 0.2 seconds for most of the planned tests. Since the Fastax camera provides several hundred feet of useable film with a 400-foot magazine, a wide range of framing rates was available for test coverage.

A framing rate of between 1,500 and 3,000 frames per second was found to be excellent for these studies, with most of the tests conducted at about 1,700 frames per second. At this framing rate all of the necessary bubble behavior was covered and the image was sufficiently sharp and clear. Within the above range of framing rates, adequate lighting can be provided by direct sunlight. For some tests, a sheet of white Celotex placed behind the tank served as a reflector and improved the brightness of the field of view. The film used was Ektachrome EF with standard processing.

SYNCHRONIZATION OF THE TWO-CAMERA SYSTEM

The timing arrangement used to synchronize operation of the two cameras, operation of the electronic flash unit, and detonation of the explosive is shown in the diagrammatic sketch of Fig. 4. The time values as given are representative of an actual test. A single starting button is used to initiate both the Fastax and the Cordin systems. Once started, the two camera systems operate independently of each other. The Fastax system involves a delay timer and the Fastax camera. The Cordin system includes the Cordin camera unit, the electronic flash unit, and the detonator.

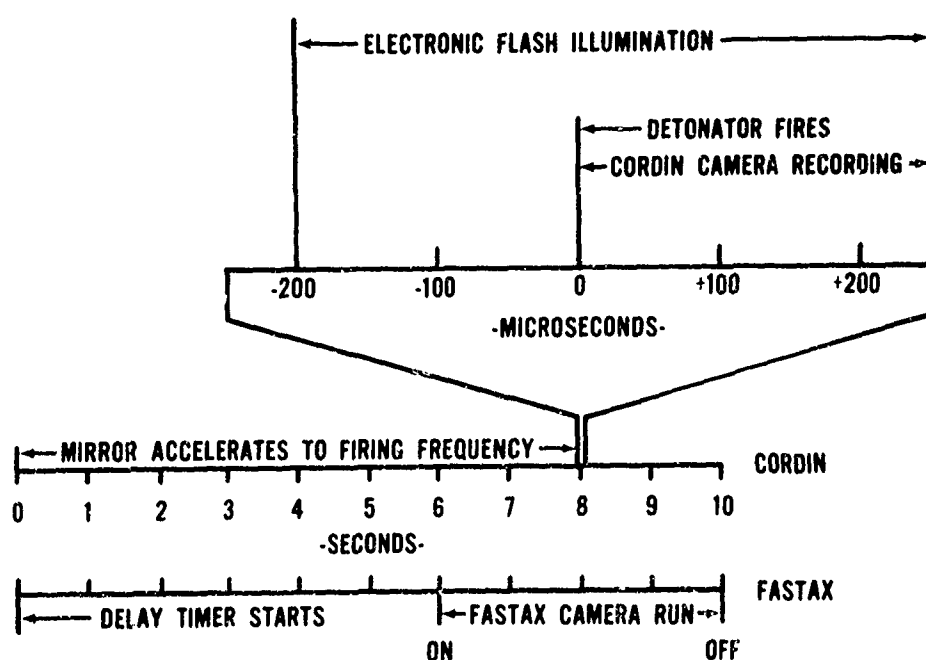


FIG. 4. Diagram of Timing Arrangement.

As shown in Fig. 4, both camera systems are started simultaneously. The start button initiates a delay timer in the Fastax system which after a 6-second delay starts the Fastax camera. The camera takes about 2 seconds to attain the required film transport speed (and required framing rate), and will run for a total of about 4 seconds. The actual framing rate at any given time can be post-event determined from milli-second timing marks recorded on the film.

For the Cordin camera system, proper recording of the event requires synchronization between the camera, external shutter, operation of the light source, and initiation of the test round. Only 10% of the rotational time of the camera is actual recording time; the other 90% is blank time since the mirror sweep doesn't engage the film. The Cordin camera has a mechanical shutter with a speed of about 1/50 second. However, for studies of the present type it can be treated as an open-shutter camera with the blank periods used for starting and stopping the event. In the present studies, shuttering was accomplished by activating the light source during the prerecording portion of the sweep and quenching the light either directly at the end of the recording time or during the post-recording portion of the sweep so as to prevent multiple exposure of the film.

For the Cordin camera, a time interval of 8 seconds is allowed for the mirror unit to attain the required rotational velocity. The events then follow the sequence of timing as shown in the enlarged scale portion of Fig. 4. The zero time on the microsecond scale represents the

time at which the Cordin camera starts recording; that is, the time at which the mirror sweep first engages the film. At that same instant, or slightly before or after depending on the time requirements of the test, the detonator is fired. As shown on the scale, 200 microseconds before the start of the recording time the flash unit is activated during the prerecording phase of one mirror rotation. This 200-microsecond delay allows the light intensity to reach a constant value. The light is then quenched by a signal from the camera unit some 250 microseconds after the zero time when the mirror sweep enters the postrecording phase.

DISCUSSION OF AN UNDERWATER TEST

EXPERIMENTAL ARRANGEMENT

In order to describe the type of camera records which can be obtained by the two-camera arrangement, one specific test will be discussed in terms of both the Cordin system and the Fastax system results. The purpose at this time is to highlight those aspects of the dynamic behavior which are associated with the microsecond and millisecond time ranges, and are thus recorded by the Cordin and Fastax systems, respectively.

The plan layout for this underwater test was similar to that shown in Fig. 1. The instrumentation arrangement has already been described. The objects in the water tank are a detonator, a small air-filled balloon, and a piece of glass plate which was suspended behind (but not touching) the balloon. A side view of the tank as seen by the cameras is shown in Fig. 5. The approximate distances from the detonator to the balloon surface, and from the balloon to the glass plate, were about 3.4 inches and 1 inch, respectively. The glass plate was 5 inches wide by 7 inches long by 3/32-inch thick, and was suspended in the water by two pieces of thin cord. The synchronization timing was that shown in Fig. 4. The Cordin camera operated at 100,000 fr/sec, and the Fastax camera at 1,680 fr/sec.

CORDIN CAMERA RECORDS

The main features shown by the Cordin camera records are the behavior of the pressure pulse and the formation of a cavitation field. Records show the pressure pulse propagating outward from the explosion point as a spherically expanding front, with the curvature being modified for that portion of the wave which impinges against the balloon and the plate. When the pressure pulse strikes the surface of the balloon, it is reflected as a rarefaction front, with a cavitation field formed between the reflected front and the balloon membrane. The rarefaction front, in turn, impinges against the gas bubble which is still in an early stage of expansion, and a secondary reflection is produced.

At a framing rate of 100,000 fr/sec, the Cordin camera records covered about the first 250 microseconds of the underwater event. Figure 6

shows a sequence of the first 20 frames taken with the Cordin camera. The first frame shows the underwater objects in silhouette just prior to the firing of the detonator. The second frame shows the detonator just after firing, with the initial formation of the pressure pulse and the bubble. The remaining frames show the continuation of the underwater behavior patterns as they developed during the initial stages of the explosion. All frames in the Fig. 6 sequence are 10 microseconds inter-frame with an effective exposure time of about 3 microseconds. The pictures from the Cordin camera records show the underwater objects laterally reversed from the relative orientation shown in Fig. 5. This is due to the use of internal mirrors in the Cordin camera which laterally reverse the image. This can be readily corrected through the use of one additional external mirror, but was not deemed necessary in the present studies.

One of the advantages in using the shadowgraphy technique with the Cordin camera is the fine detail which can be obtained with color film. Much of the detail evident in the original frames used in Fig. 6 has been lost in the transfer to black and white, and further so in size reduction to accommodate a manuscript page. In an attempt to demonstrate the color advantages of the Cordin camera-shadowgraphy technique, Fig. 7 through 9 are reproduced in color, and are enlargements of frame numbers 2 and 5; 9 and 11; and 14 and 17; respectively.

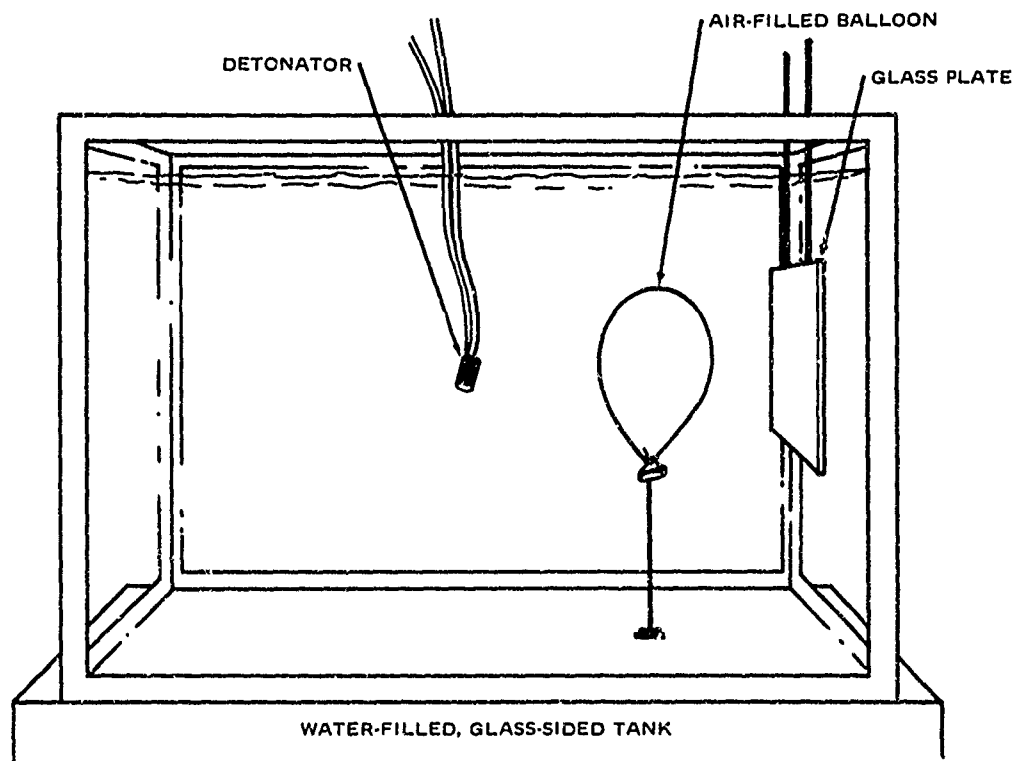


FIG. 5. Camera View of Experimental Field in Water Tank.

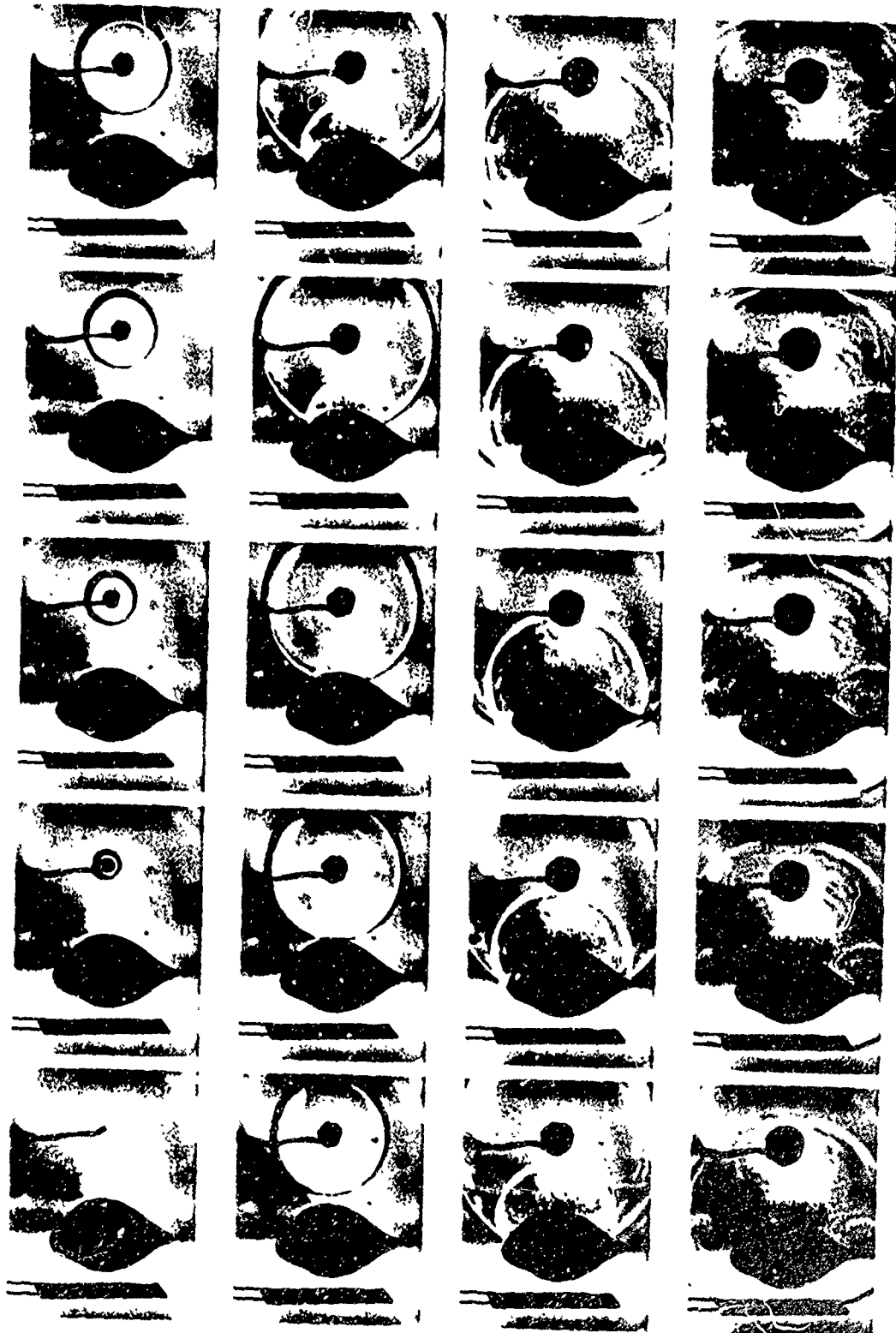


FIG. 6. First 20 Frames of Cordin Camera Sequence.

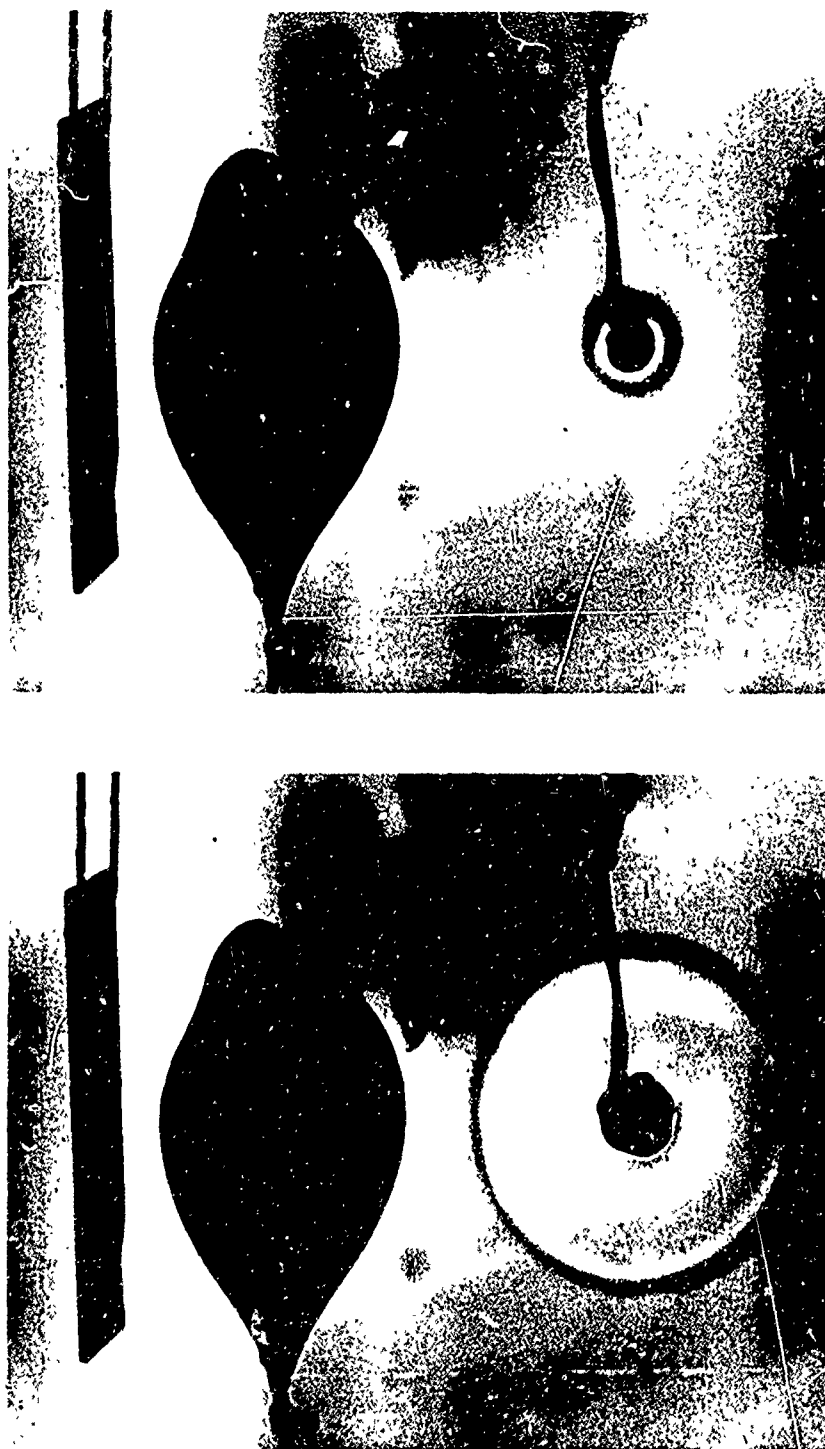


FIG. 7. Growth of Pressure Pulse: Cordin
Frames 2 (upper) and 5 (lower).

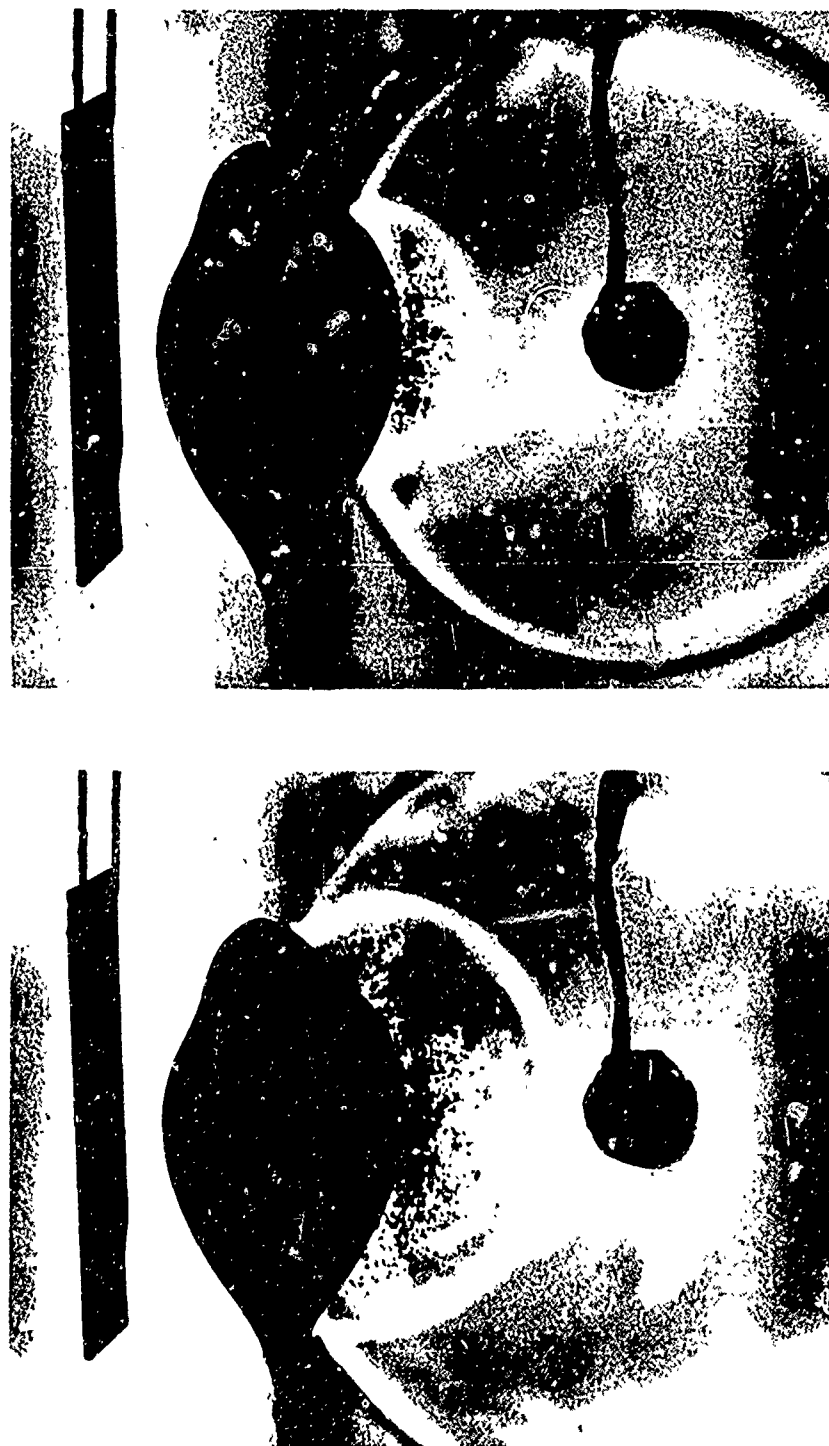


FIG. 8. Reflected Pulse and Cavitation Field:
Cordin Frames 9 (upper) and 11 (lower).

Figure 7 shows the initial growth of the primary pressure pulse. The upper picture in Fig. 7 shows the first Cordin frame after initiation of the detonator. The pressure pulse and the gas bubble are both in the first stage of formation. The lower picture in this figure shows the event 30 microseconds later.

Figure 8 shows the formation and growth of the cavitation field due to the pressure pulse reflecting from the balloon surface. The upper picture in Fig. 8 shows the cavitation field between the rarefaction front and the balloon surface, about 20 microseconds after initial impingement of the pressure pulse against the balloon. The lower picture shows the continued growth of the cavitation field 20 microseconds later (40 microseconds after initial impingement).

Figure 9 shows the experimental field in later stages of behavior. In the upper picture of Fig. 9, the reflected front has encountered the gas bubble and a secondary reflection has occurred. The balloon has also acted as a wave shaper, changing the curvature of a portion of the pressure pulse. In the lower picture the primary pulse has passed the plate producing a very low intensity reflection which is moving from the plate toward the balloon. The upper and lower pictures in Fig. 9 show the cavitation field at times of 70 and 100 microseconds, respectively, after initial pressure pulse impingement.

It should be noted that the entire Cordin sequence was completed before the primary pressure pulse impinged on the glass viewing sides of the tank. When the pressure pulse strikes the tank wall, it is reflected in much the same manner as from the surface of the balloon, the reflection producing a cavitation field near the inner surface of the viewing wall. This cavitation field, which covers the entire wall of the tank, drastically reduces the clarity and detail of the events occurring in the tank. Such a cavitation field lasts for about 1 millisecond or longer and needs to be considered when planning the timing and synchronization of the underwater event. Although not specifically described in this paper, Cordin camera records of this type can be used to obtain quantitative values of such features as the pressure-time history of the primary pulse at some given distance from the detonator, pressure values at different distances from the detonator, and other aspects of the explosion phenomena.

FASTAX CAMERA RECORDS

The main features shown by the Fastax camera records relate to the explosion bubble behavior and its effect on the surrounding underwater field. The explosion bubble goes through an oscillatory and migratory process and puts surrounding water in motion. An oscillatory behavior is induced in the balloon causing it first to expand and then to undergo an initial collapse. During the expansion phase following its first minimum condition, the balloon bubble breaks the glass target plate. Following this the balloon bubble continues to oscillate, being slightly out of phase with the explosion bubble.

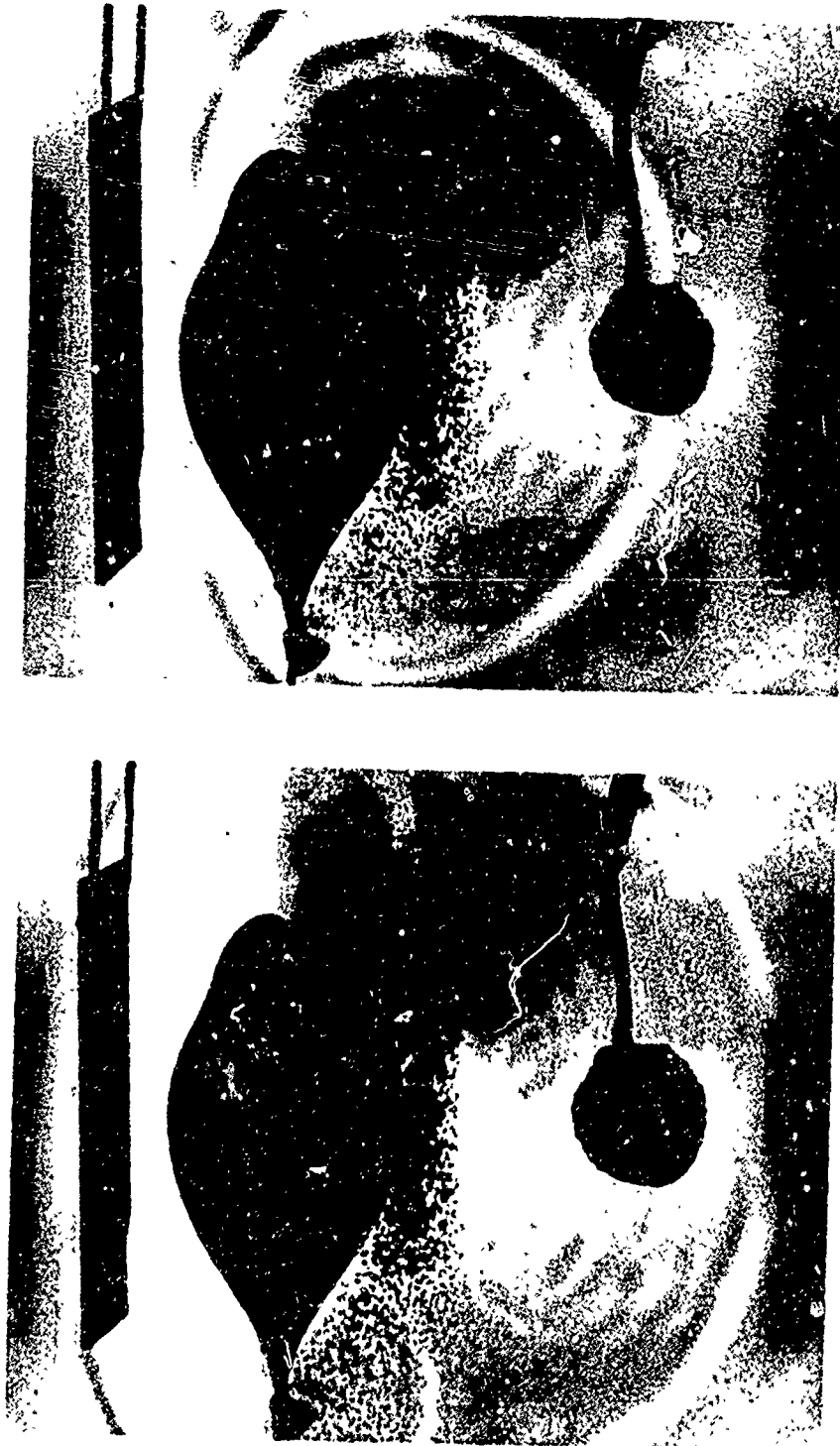


FIG. 9. Later Stages of Pulse Behavior: Cordin
Frames 14 (upper) and 17 (lower).

At a framing rate of 1,680 frames per second the main events as viewed from the Fastax records are over in about 200 frames or approximately 120 milliseconds. It is interesting to note that the entire Cordin sequence is recorded in less than one interframe of the Fastax run. Several of the Fastax frames are reproduced in black and white to illustrate highlights of the millisecond behavior patterns.

Figures 10 through 17 are black and white reproductions made from individual frames of the 16 mm Fastax color film. Some detail has been lost in changing from color to black and white. Each figure is identified by its frame number in the framing sequence, with frame number 1 recording the initiation of the detonator. At a framing rate of 1,680 frames per second, the interframe time is approximately 0.6 millisecond, and each frame has an exposure time of about 0.2 millisecond.

Figure 10 is frame number 3 in the Fastax sequence. It shows the obscuration of the detonator bubble and the targets by cavitation fields formed at the inner surfaces of the tank walls. Side wall cavitation was present in frames 2 and 3, and apparently lasted for somewhat longer than a millisecond. In the present tests it was an interesting phenomenon, but did not interfere with the overall viewing.

Figure 11 (frame 10) shows the detonator bubble approaching its first maximum. Water displacement appears to have dimpled the front surface of the balloon and pushed the back surface into contact with the plate. One side of the bubble is slightly flattened, probably due to the unequal rate of water displacement due to the presence of the balloon and plate.

In Fig. 12 (frame 28) the detonator bubble has passed its first maximum and is in the first collapse phase. The balloon has also passed its initial maximum condition and is in the start of its collapse phase. At this time the flattening of the detonator bubble is much more pronounced. In this figure the glass plate has been displaced to the right by the action of the balloon. One of the most interesting aspects of this particular test was the relationship between the oscillations of the detonator bubble and the unsymmetrical oscillatory gyrations of the balloon.

In Fig. 13 (frame 33) the detonator bubble is near its first minimum, while the balloon is still collapsing. Two frames later (Fig. 14), the balloon has reached its first minimum condition while the detonator bubble has started its second expansion. The balloon appears to have broken prior to reaching its first minimum, and thereafter it appears as a gaseous bubble.

After passing its first minimum the balloon bubble begins an expansion process. It is early in this expansion phase that the balloon bubble breaks the glass plate, as shown in Fig. 15 (frame 41). During this phase of behavior the balloon bubble is considerably larger than the detonator bubble.

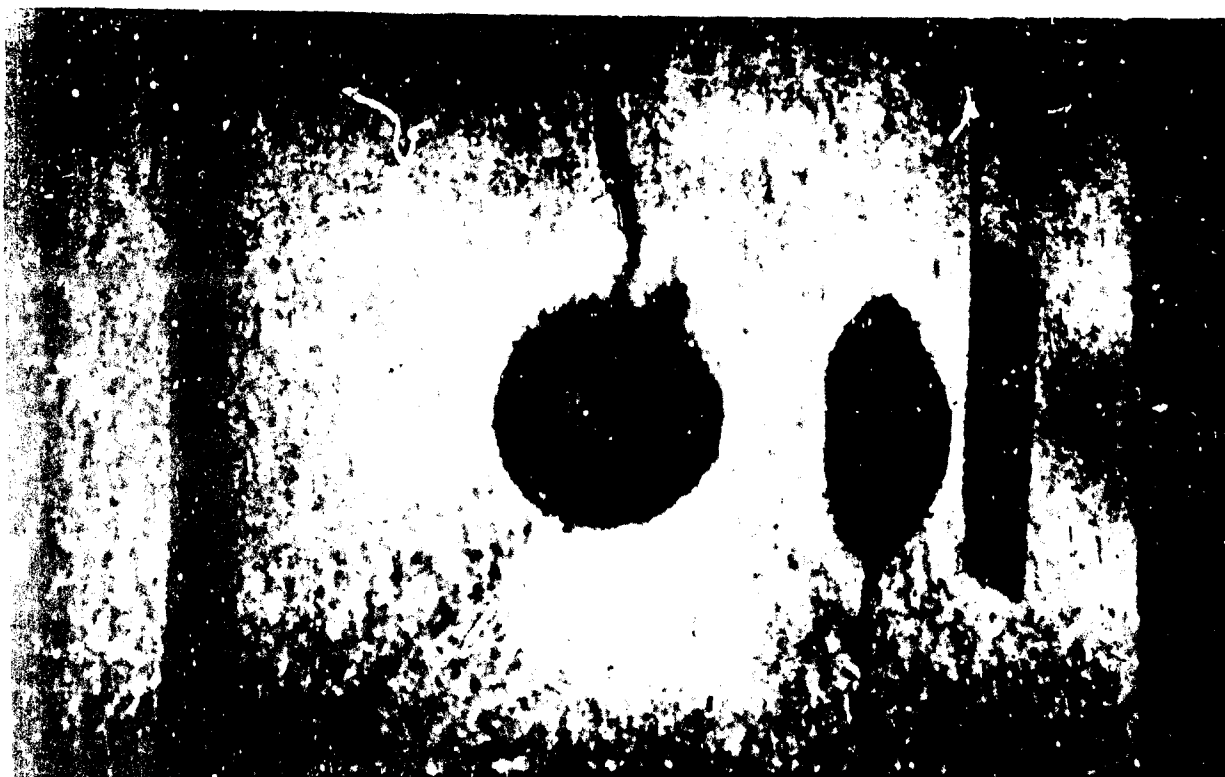


FIG. 10. Cavitation at Tank Wall (Fastax Frame 3).

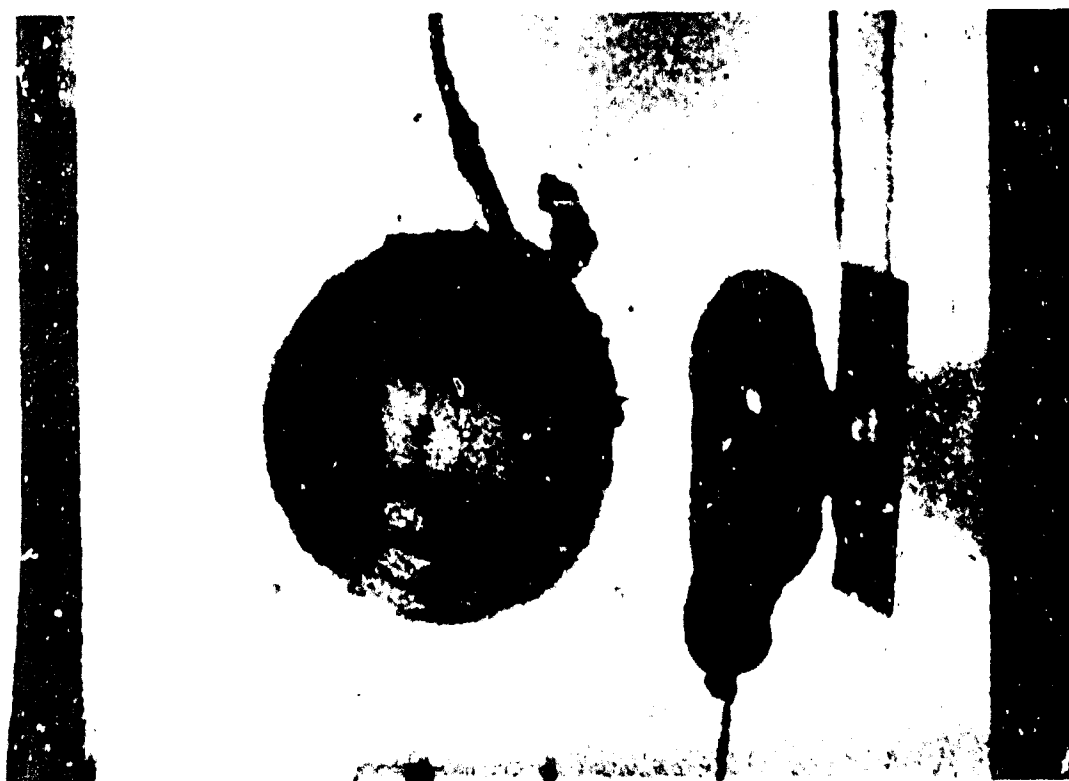


FIG. 11. Detonator Bubble Near First Maximum (Fastax Frame 10).



FIG. 12. Detonator Bubble in First Collapse Phase (Fastax Frame 28).



FIG. 13. Detonator Bubble Near First Minimum (Fastax Frame 33).



FIG. 14. Balloon Bubble at First Minimum (Fastax Frame 35).



FIG. 15. Balloon Bubble Breaking Glass Plate (Fastax Frame 41).



FIG. 16. Bubbles Joined Through Tunnel Effect (Fastax Frame 44).



FIG. 17. Lateral Displacement of Detonator Bubble (Fastax Frame 141).

By frame 44 (Fig. 16), the detonator bubble and the balloon bubble have joined by means of a tunnel effect, and there appears to have been a transfer of gaseous products between the two bubbles. After this, the lateral displacement of the detonator bubble increases and by frame 141 (Fig. 17) the center of the detonator bubble has moved about 9.5 inches to the left of its original position.

CONCLUSIONS

The two-camera system described in this report is excellent for covering both the microsecond and millisecond behavior patterns of a small underwater explosion. Through variations in the framing rates for the two cameras, and changes in the synchronization timing, the system is quite versatile for the study of different phenomena related to the explosion and to target response. It is a relatively simple system which requires a minimum of setup time, and thus lends itself to use with large numbers of small-scale tests.

One of the most interesting aspects of the test described in the report was the breaking of the glass plate due to the action of the balloon bubble. A counting of the frames indicates that the balloon collapsed to a minimum about 21 milliseconds after detonation. The plate began to break during the initial phase of the balloon bubble expansion, or about 1 millisecond after the minimum condition was reached. Quite simply, the oscillatory effect of the detonator bubble put the water in motion. Energy of the water motion appears to have been concentrated by the low-density region of the balloon and brought to bear against the adjacent glass plate, destroying it. It is instructive to note that other tests have demonstrated that if the balloon was not present, the detonator explosion would not have broken the glass.

This simple means of energy transfer should have a number of unique applications in commercial metalworking operations where underwater explosives are involved. In many such operations it has been customary to associate the deformation processing of the part solely with the action of the primary pressure pulse. Simple experiments such as the one described here demonstrate that the bubble effect and the resulting gross water motion can play a significant role in the working of the target piece.

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