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THE PHYSICAL EFFECTS OF CONVENTIONAL EXPLOSIONS ON THE OCEAN ENVIRONMENT

By
George A. Young

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NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

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13 ABSTRACT

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UNDERWATER EXPLOSIONS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
NAVAL ORDNANCE LABORATORY
SILVER SPRING, MARYLAND

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THE PHYSICAL EFFECTS OF CONVENTIONAL EXPLOSIONS ON THE OCEAN ENVIRONMENT

Most of the research on the phenomena of underwater explosions has been directed toward the immediate close-in effects, with relatively limited attention given to the changes that might occur in the environment over a long time-scale or at some distance from the actual point of explosion. In most cases, data or information that might be relevant to environmental influences has appeared in classified reports or in publications with other primary objectives. This report has been written to consolidate such material and to incorporate other data acquired at the Naval Ordnance Laboratory during a period of over twenty years of underwater explosion research. For current purposes, it should be treated as an interim report to be used for guidance until more definitive studies have been conducted.

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ROBERT ENNIS
Captain, USN
Commander

C. J. ARONSON
By direction

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I INTRODUCTION

The physical phenomena of underwater explosions have been investigated extensively for military purposes and, to a lesser degree, for a number of scientific or industrial applications, such as seismic surveying. In the military studies, the research effort has been directed mainly toward the damaging effects that occur for a brief interval of time within a relatively short distance of a conventional or nuclear explosion. On the other hand, a geophysical prospector is not concerned with close-in effects, but he uses an underwater explosion as a source of a shock wave. This wave soon acquires acoustic properties, and a complex signal is recorded at a distance, resulting from wave propagation through the water and through various layers of bottom material.

Very little attention has been given to the effects of conventional explosions on the environment, except for studies of the number of fish killed (e.g., Tiller and Coker, 1955). Although there is no doubt that fish in the vicinity of an explosion can be stunned or killed, the number obviously depends on the location and the season, and this can be reduced by careful scheduling of experiments and by checking the vicinity for fish with an echo sounder just prior to firing a charge. If fish are nearby, it might be possible to lure them away with an acoustic signal (Maniwa, 1970).

This report, however, is not concerned with biological aspects, but with the physical effects of underwater explosions that might have some influence on the undersea environment. Particular attention will be given to the heating of water by an explosion, the mixing of explosion products with water, and cratering by explosions on or near the seabed. Information of this type might prove useful for the evaluation of possible biological effects over a longer time-scale than that involved in the immediate killing of fish. It is not clear at this stage if these long-period effects would be harmful, beneficial, or entirely negligible.

II SHOCK WAVE HEATING OF THE ENVIRONMENT

In order to evaluate the physical effects of explosions on the environment, it is helpful to separate the phenomena into those related to the shock wave and those related to the explosion products. These phenomena have been described by Cole (1948). His publication includes similitude equations and other relationships useful for evaluating the physical effects of conventional explosives such as TNT.

For example, Figure (1) shows the peak shock wave pressure vs distance curves for 125-pound Pentolite and TNT explosions in water. These compositions are presented because they are frequently used and because the data are in the open literature. It will be noted that the pressure drops off rapidly with distance in the vicinity of the charge and that a power law relationship exists beyond a distance of about eight feet. The distance at which a given peak pressure is found is proportional to the cube root of the charge weight; for example, the distance scale of Figure (1) would be doubled if calculations were made for 1000-pound charges. Ultimately, the energy in the shock wave is degraded into heat, and the transformation should result in an increase in the temperature of the water (Cole, 1948). However, in terms of military and environmental effects, this is doubtless negligible at large distances from an explosion.

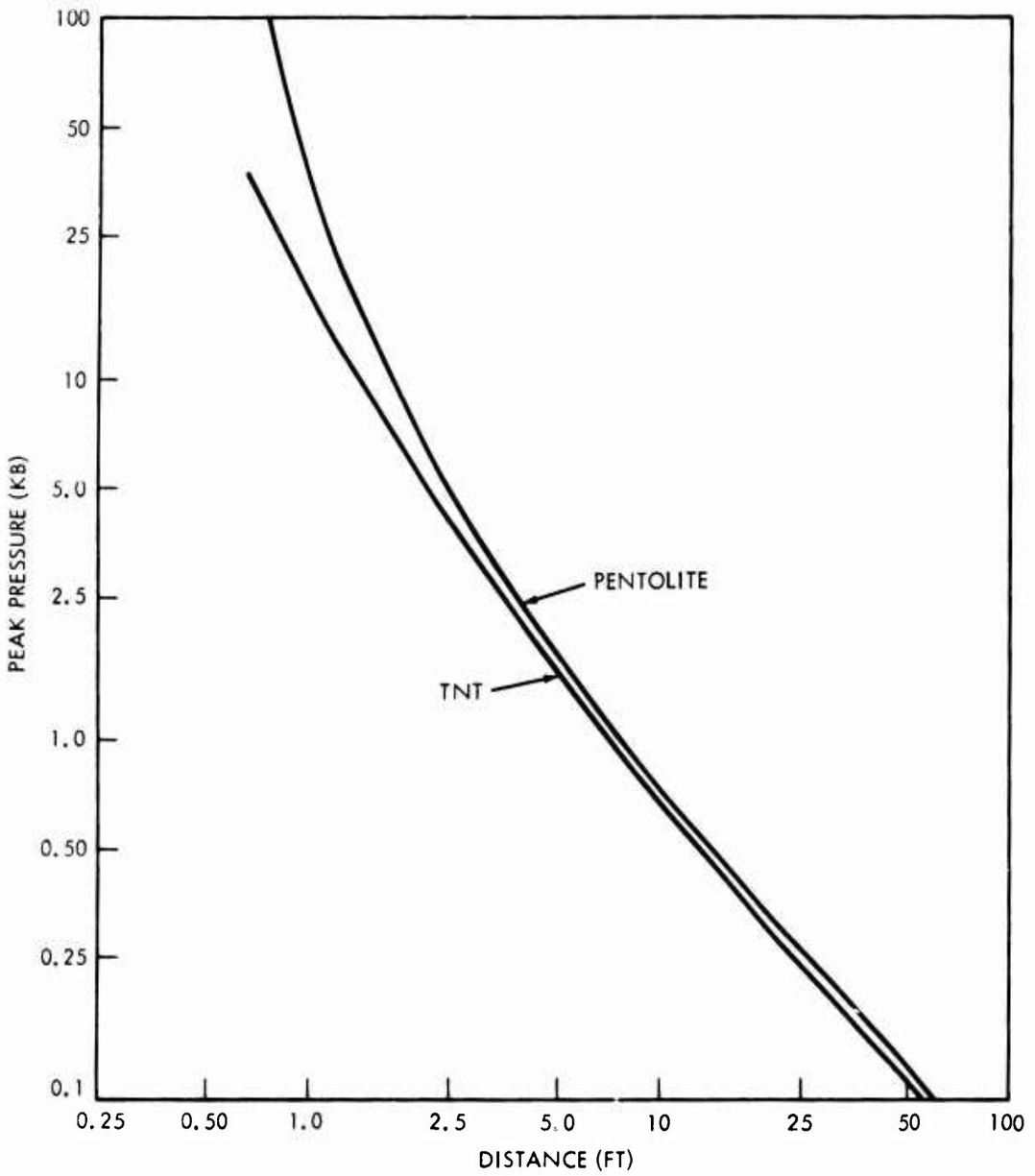

FIG. 1 PEAK SHOCK WAVE PRESSURE VS DISTANCE FOR 125-LB PENTOLITE AND TNT UNDERWATER EXPLOSIONS

On the other hand, the dissipation of shock wave energy close to an explosion is rapid, and it results in the loss, or "wastage" of possibly 25% of the total explosion energy within 25 charge radii of a TNT burst (Cole, 1948). This results in significant irreversible heating of the water in the vicinity of the charge. Figure (2) shows the net temperature increase in water after the passage of an intense shock wave. The values shown in the figure were taken from calculations by Penney (1940), and Walker and Sternberg (1965), and from a classified publication by Snay, Butler, and Gleyzal.

Figure (3) shows the net temperature rise vs distance from 125-pound TNT and Pentolite explosions, obtained by combining the information given in Figures (1) and (2). It is clear that, after the shock wave has gone by, the products of an explosion are surrounded by a volume of heated water. In some cases, a thin shell of steam will be formed at the interface of the explosive charge as a result of shock wave heating combined with the effect of heat conduction and radiation from the explosion (see Section IV). However, the latter effects are negligible, and shock wave theory adequately accounts for the heating and possible vaporization of the water (Arons and Yennie, 1948).

Figure (4) gives the volume of water heated as a function of charge weight for net temperature changes of at least 10 C, 1 C, and 0.1 C. This volume is directly proportional to the charge weight for a given explosive.

At peak pressures less than one kilobar, the shock wave behavior resembles that of an acoustic wave, and the passage of the wave results in thermodynamically reversible changes, except for very minor losses of energy resulting from viscosity.

III BUBBLE AND SURFACE PHENOMENA

Although the shock wave heating of water can be calculated from theory, the subsequent history of the heated volume cannot be determined on the basis of theory alone. Immediately following an explosion, the products exist in the form of a plasma at a high temperature and pressure. The products expand at an extremely rapid rate, and, when the radius of the spherical "bubble" is equal to two to three charge radii, the mixture reaches an equilibrium composition and starts to behave like an ideal gas. The bubble continues to grow and it achieves a relatively large volume, at which time the contents reach a low temperature and a pressure less than the hydrostatic pressure of the environment.

The water heated by the shock wave is pushed out by the expanding gases, and the thickness of the warm layer should decrease until the maximum bubble radius is reached. When the bubble then collapses to a minimum size, the thickness of the heated layer should increase; however, processes occur at this stage that can lead to turbulent mixing of the bubble contents with the surrounding water.

The first of these is termed Taylor Instability. The importance of this in explosion phenomena was first pointed out by Taylor and Davies (1943), who stated that the surface of a bubble should be smooth and stable during the first expansion and the early part of the first contraction, but should become unstable when the gas pressure rises and the inward radial motion of the water is decelerated. This results in the formation of small jets of water which are injected into the bubble at the time of collapse. The jets doubtless break into a spray, which evaporates and cools the contents of the bubble, resulting in a change in composition and a loss of bubble energy.

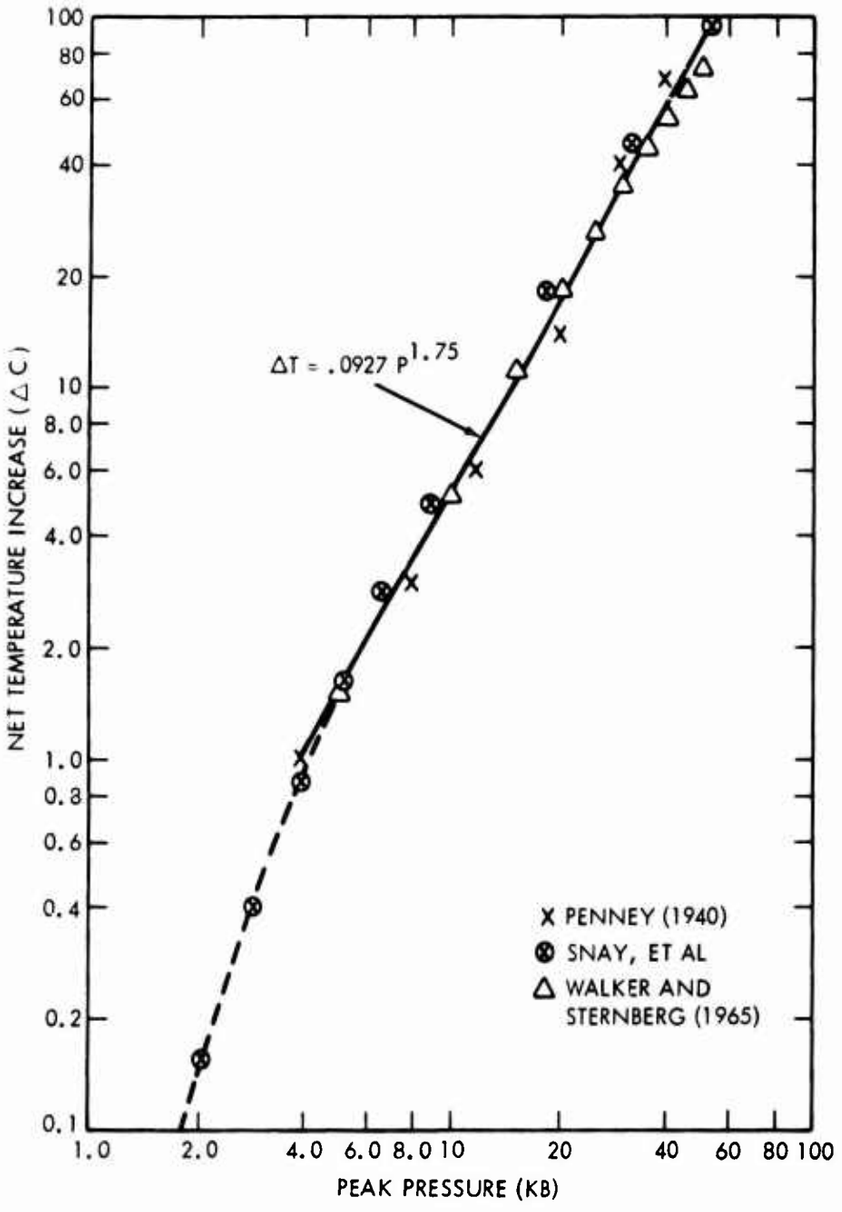

FIG. 2 NET TEMPERATURE INCREASE DURING SHOCK WAVE PASSAGE

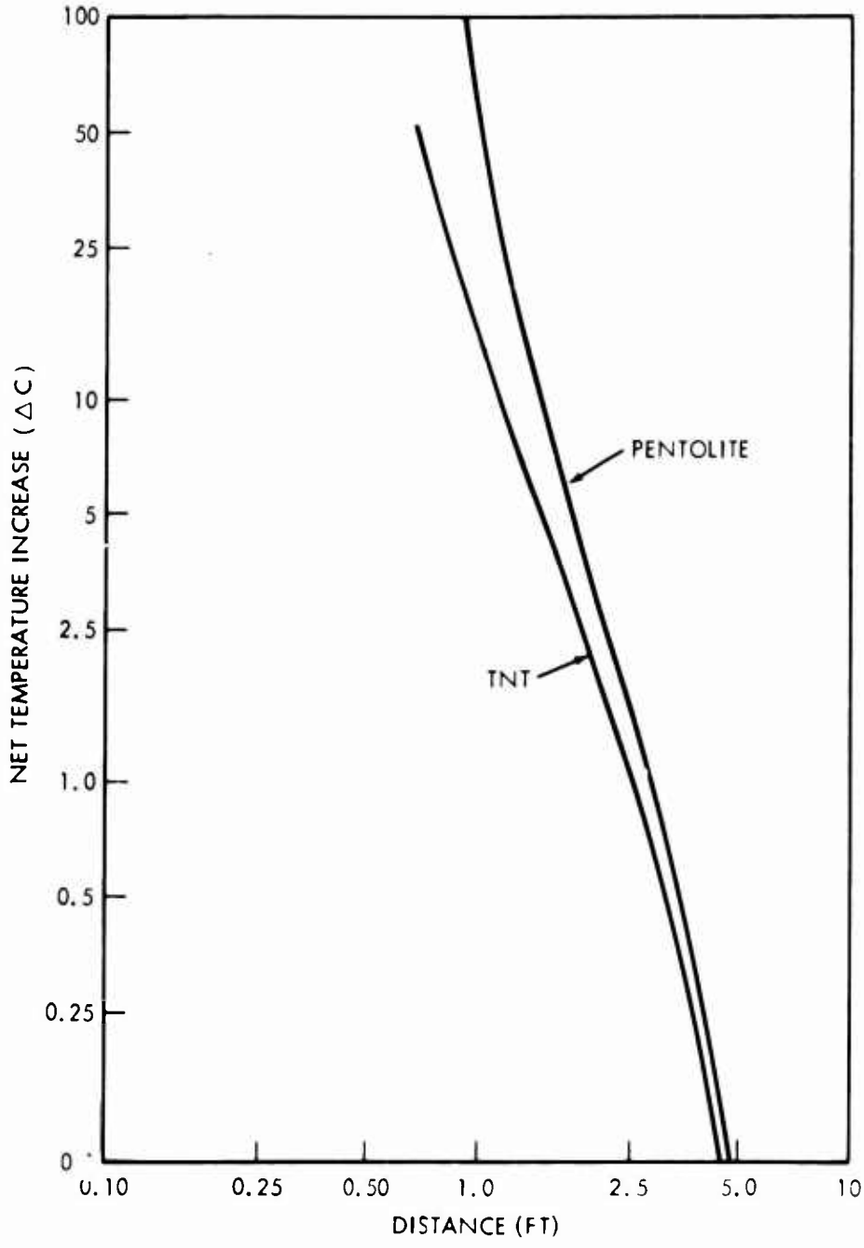

FIG. 3 NET TEMPERATURE INCREASE VS DISTANCE FOR 125-LB PENTOLITE AND TNT EXPLOSIONS

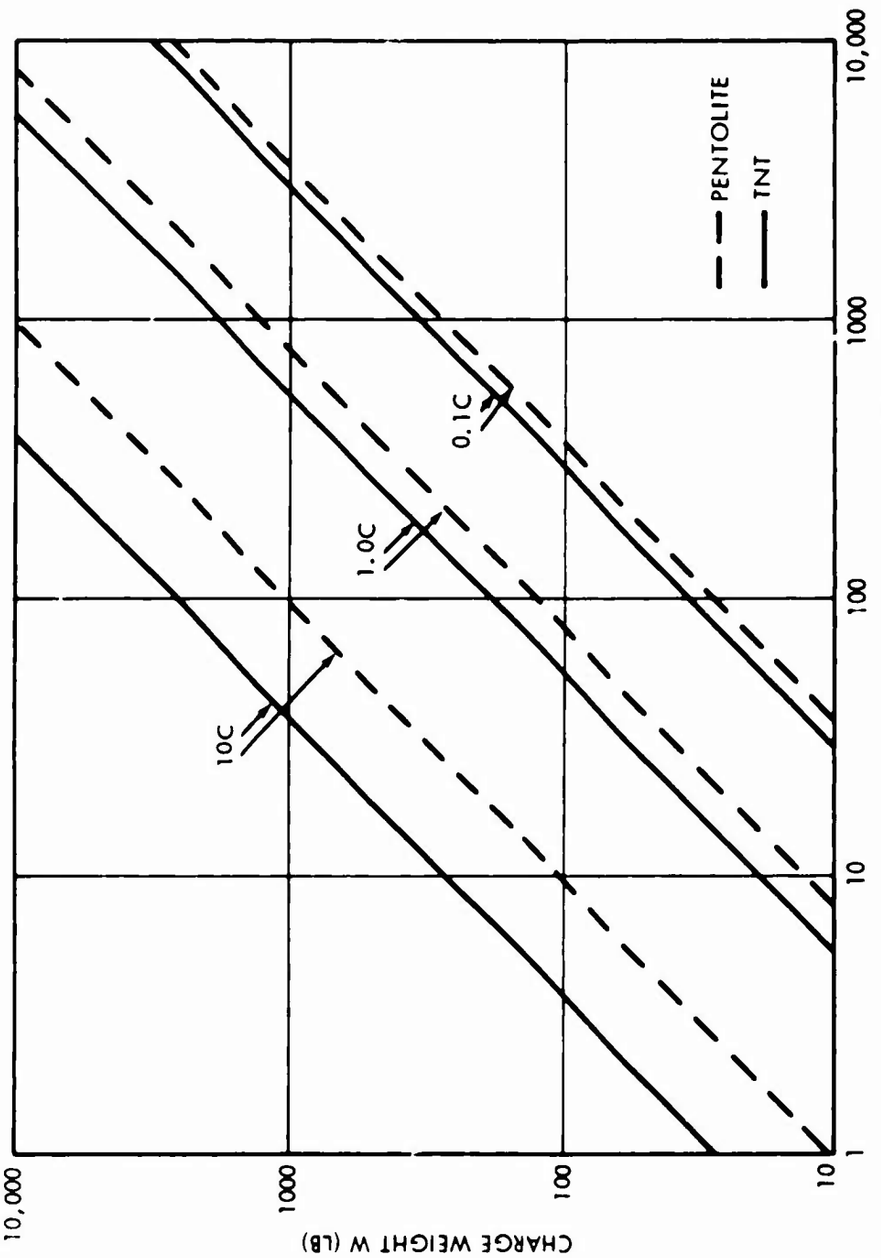

FIG. 4 VOLUME HEATED BY THE SHOCK WAVE FROM PENTOLITE AND TNT EXPLOSIONS

A second process that can lead to turbulent mixing is the larger scale jetting that occurs when an explosion bubble migrates toward the surface.

In this case, as the bubble collapses to a minimum size, the bottom of the bubble moves inward faster than the sides or top, and the bottom rises in the form of a turbulent jet that may strike the top and penetrate the water above the bubble. Mixing can occur along the boundary of the jet, and the impact of the jet on the bubble interface probably generates a cavity and causes the ejection of a certain amount of spray into the bubble. Figure (5) is a sketch of this process, based on photographs of small-scale experimental studies in tanks.

The first collapse of an explosion bubble is the most energetic, and it probably results in the greatest mixing of bubble contents with the environment. During the subsequent migration of a bubble, the pulsations gradually become weaker, and the bubble develops an internal circulation. It resembles a spherical vortex at this stage. Eventually, the circulation stops, and the bubble acquires a hemispherical shape*. It gradually erodes at the rear while the leading edge remains smooth. Explosion products are probably deposited in the turbulent wake of the bubble until it disintegrates into a cloud of tiny bubbles. In some cases, relatively large bubbles move out of the cloud and reach the surface first. In the deepest shots on record, the vortex becomes unstable and breaks up into a cloud of bubbles after migrating a relatively short distance. Some of these effects are shown in the photographs in Figures (6) and (7). It should be stressed, however, that the sub-surface phenomena are strongly dependent on experimental conditions and that the nature of this dependency has not been established at the present time, especially for depths greater than about 25 times the maximum bubble radius.

A good understanding of the dynamics of individual air and gas bubbles has been acquired by investigators in the field of fluid mechanics. This knowledge could be applied to explosion bubbles after they stop oscillating and reach a passive state. An early effort along these lines was made by Taylor and Davies (1944), who developed a theory for the rate of rise of relatively large air bubbles and used this to calculate the vertical velocity of a non-pulsating explosion bubble. Tiny bubbles (radius < 0.1 cm) behave like solid spheres and rise at a slower rate. A good summary of the behavior of passive bubbles, with some discussion of pulsating explosion bubbles, has been written by Lane and Green (1956).

The following equations can be utilized for calculating the time and length-scales of bubble phenomena for different weights of TNT and Pentolite. Equations of this type are basic for establishing similitude of both bubble and surface phenomena for different explosives and for modelling in special facilities such as reduced-pressure tanks or accelerated tanks (Snay, 1961).

$$A_1 = 12.6 \frac{W^{1/3}}{Z^{1/3}} \quad , \tag{1}$$

$$T_1 = 4.36 \frac{W^{1/3}}{Z^{5/6}} \quad , \tag{2}$$

* This transition may result from the breakup of the vortex and the coalescence of fragments into one large bubble.

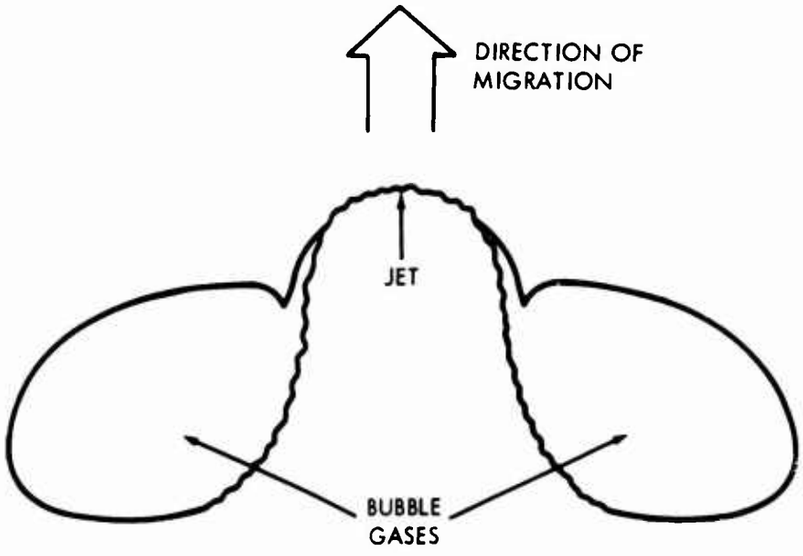

FIG. 5 BUBBLE JETTING BY A MIGRATING EXPLOSION BUBBLE

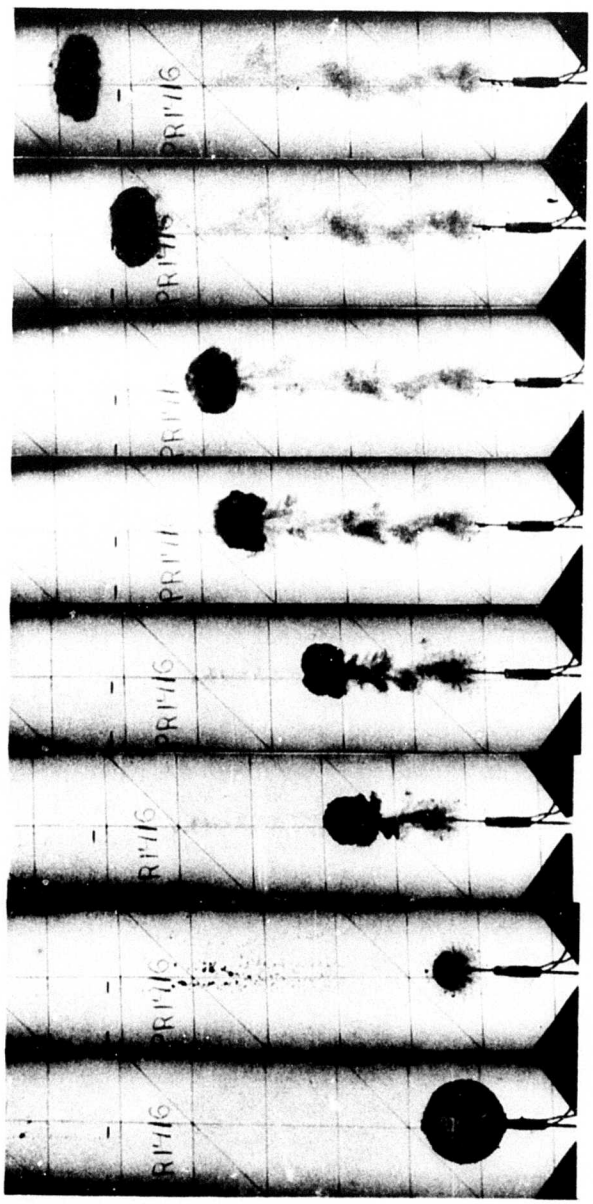

FIG. 6 BUBBLE MIGRATION IN ACCELERATED TANK EXPERIMENT - SHOT 1416

FIG. 7 BUBBLE MIGRATION IN ACCELERATED TANK EXPERIMENT - SHOT 1420

$$\Delta d = 80 \frac{W^{1/2}}{Z} \quad , \qquad (3)$$

where: A_1 = Maximum radius of the bubble during its first pulsation, ft,

W = Weight of explosive (TNT or Pentolite), lb,

Z = Hydrostatic pressure at depth of explosion, ft of water (usually $d_1 + 33$, where d_1 = depth of explosion in ft),

T_1 = Period of first bubble pulsation, sec,

Δd = Distance of bubble migration, from d_1 to depth of bubble collapse at the end of the first pulsation.

The first effects of an underwater explosion visible to an observer above the surface are the phenomena caused by the arrival of the direct shock wave at the air-water interface. The shock is reflected as a tension wave, and a layer of water is spalled off, leaving a cavitated region below it. Jets form on the surface, and the jets rapidly break up into spray as they rise in the air, as a consequence of the same Taylor Instability effect that occurs within an explosion bubble. The spray forms a white dome with a low bulk density. As the dome and other shock or pressure wave effects at the surface are not considered to have a significant influence on the environment, they will not be discussed further. A more complete description will be found in Cole (1948).

For current purposes, the surface phenomena that result from the arrival of the bubble are of primary significance because they are indicative of the nature of the transport and dispersion of explosion products. Measurements of these visible effects, combined with studies of small-scale bubble migration in tanks and other experimental and theoretical results, have led to a good understanding of the relations between above-surface and below-surface phenomena.

The following definitions have been employed in previous descriptions and have proved to be convenient for describing and interpreting explosion effects:

Smoke Crown - The roughly spherical turbulent cloud that rises above the surface following a very shallow explosion. If the explosive is TNT, for example, the smoke crown is black.

Column - The hollow cylindrical or conical sheath of water thrown upward by the expanding explosion gases after a shallow or very shallow explosion.

Plume - A relatively broad jet or spout of water that disintegrates into spray as it travels through the air. A plume resembles the stream from a fire hose, and always has a dense fluid core. Plumes may rise vertically or may move outward at an angle with the vertical. The latter are termed radial plumes.

Jet - The central plume that rises vertically above the column on shallow bursts.

Base Surge - A toroidal cloud that forms when the column and plumes collapse and break up into spray. The base surge expands radially along the surface of the water.

Mound - In this case, the water surface rises into a smooth mound that subsides rapidly and spreads out laterally. The mound may be roughly hemispherical or dome shaped. Some slight roughness may be observed, but no plume formation occurs.

Upwelling - A rising current of water that contains explosion products and spreads out laterally at the surface. Radial expansion can be clearly seen. No elevation or depression of the surface occurs.

Diffusion - Explosion debris becomes visible at the surface, but appears gradually and does not spread out. No water circulation is visible. The debris or tracer may be beneath the surface but close enough to be visible.

It is useful to categorize explosion depths in relation to the first maximum bubble radius (Equation 1), or in relation to the distance traversed by the bubble when it migrates. A shallow explosion is one at a depth, d_1, less than A_1, while explosions at greater depths are considered to be deep. If an explosion is deep enough to permit the bubble to oscillate three or more times before reaching the surface, it is termed "very deep". If no visible effects appear at the surface, the explosion is said to be contained.

This system is less satisfactory for explosions near the surface, because the phenomena change drastically with small changes in depth; however, for the purposes of this report, an explosion at a depth less than $0.20\ A_1$ will be considered to be very shallow.

As the most complete set of surface phenomena data available is for 300-pound charges of Pentolite and TNT, these will be described quantitatively. Subsequently, methods of converting these data to other charge weights or depths will be presented. When a 300-pound explosion occurs at a depth of two feet ($d_1 = 0.08\ A_1$), a black smoke crown is one of the dominant features at early times. The crown attains a width of about 150 feet. It forms above an almost perfectly cylindrical white column that reaches a maximum diameter of about 45 feet and a height of about 60 feet. A central jet emerges above the smoke crown and rises to a height of possibly 450 feet (ten times the column diameter). It seems to carry a considerable amount of the smoke along as it rises. The maximum height is attained within five seconds, and the water and smoke then settle back. The finer particles and droplets may be carried several hundred feet downwind.

At a depth of 10 feet (Figure 8), a 300-pound explosion produces a roughly cylindrical column of spray, which reaches a height of about 400 feet and attains a diameter of about 150 feet prior to its collapse. The column contains a central liquid jet that is visible at the top at early times and is more clearly seen when the column begins to collapse. At about 1.1 seconds after the burst, a group of low radial plumes emerges from the base of the column. These plumes are clearly defined by 1.5 seconds. With increasing depth of explosion, the vertical column shrinks in size, but the central liquid jet becomes well-defined and rises above the column. However, the overall jet height decreases. The radial plumes that emerge from the base become larger with increasing depth, although the time of origin remains about the same. At an explosion depth of 19 feet, the central

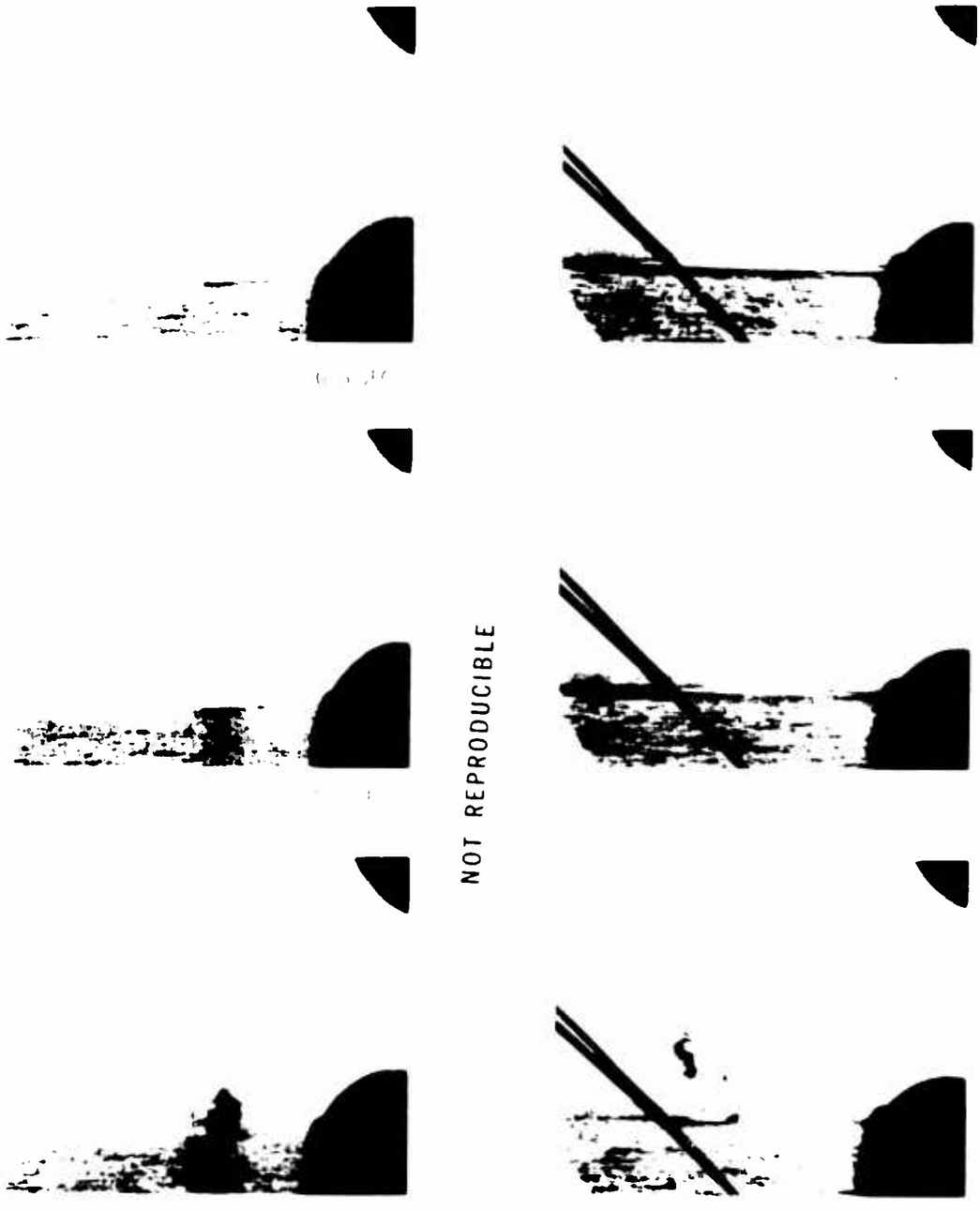

FIG. 6 PLUME PHENOMENA OF SHALLOW AND DEEP

column and jet are rapidly overtaken by the radial plumes, which appear at about one second, and by two seconds after the explosion only a large hemispherical mass of radial plumes is visible. This trend continues to an explosion depth of at least 22 feet, where the overall height becomes only about 160 feet and radial plumes predominate. This depth is almost exactly equal to the first maximum bubble radius.

On these shallow bursts, the explosion bubble is elongated, and its top rises above the surface. This appears externally as a cylindrical column of water covered by spray, and at an early stage of the expansion of the column, a strong vertical flow of water develops. This flow converges at the top of the column and forms a narrow vertical jet. The upper central jet, or plume, rises to relatively great heights, with the maximum observed when the depth of burst is between one-third and one-fourth of the calculated maximum bubble radius.

At a depth of 25 feet ($d_1 = 1.15\ A_1$), a definite change occurs in the surface phenomena of 300-pound explosions. The spray dome remains smooth and rounded until a vertical plume appears at a relatively high velocity about 1.10 seconds after the explosion. Radial plumes emerge at about the same time but do not reach as great a height as the vertical plume, which may rise to almost 300 feet. At a 30-foot depth, the plumes are predominantly vertical, but the total height is reduced somewhat. The height decreases steadily with increasing depth and possibly reaches a minimum of about 190 feet at a firing depth of 45 feet (Figure 8), where the plumes are mostly radial ($d_1 = 2.27\ A_1$).

The trend then reverses and the plumes formed by a 300-pound explosion at a depth of 55 feet resemble closely the plumes that appear following a 25-foot depth shot, except for a later time of appearance and a reduced maximum height. The tall vertical plumes from 300-pound explosions at depths of 25 and 55 feet have been attributed to the emergence of the large jets that form as a migrating explosion bubble collapses to a minimum size. If the position of the minimum is just beneath the surface, the rapidly-moving jet can easily penetrate the layer of water above the bubble. Calculations of bubble migration for 300-pound TNT charges, based on charts published by Snay and Tipton (1962), show that the bubble collapses to a minumum size at a depth of seven feet when the burst depth is 25 feet, and that the second collapse of the bubble occurs at a depth of 10 feet, when the depth of burst is 55 feet.

This effect is shown diagramatically in Figure (9). To prepare this figure, it was assumed that the bubble jet originates at the bottom of the bubble when it reaches a maximum size and then passes through the position of the bubble minimum. Curves can be drawn through these points to represent the top of the jet while it is under water. These curves can be connected smoothly with the plume height measurements made in air as functions of time for shots at depths of 25 and 55 feet.

If the gas bubble oscillates three or more times before reaching the surface, this effect does not occur, and no vertical plume development is observed. Nevertheless, sufficient energy remains so that the emerging bubble generates a large mass of radial plumes, as shown in Figure (10). At a depth of 100 feet ($d_1/A_1 = 6.06$), a 300-pound explosion results in the arrival of a rough mound that rises above the surface and then erupts into a large number of plumes. With increasing depth of burst, the bubble arrives at the surface in a more passive state, and it eventually produces a smooth hemispherical mound. Figure (11) shows the formation of such a mound by a 50-pound Pentolite explosion at a depth of 100 feet ($d_1/A_1 = 8.85$).

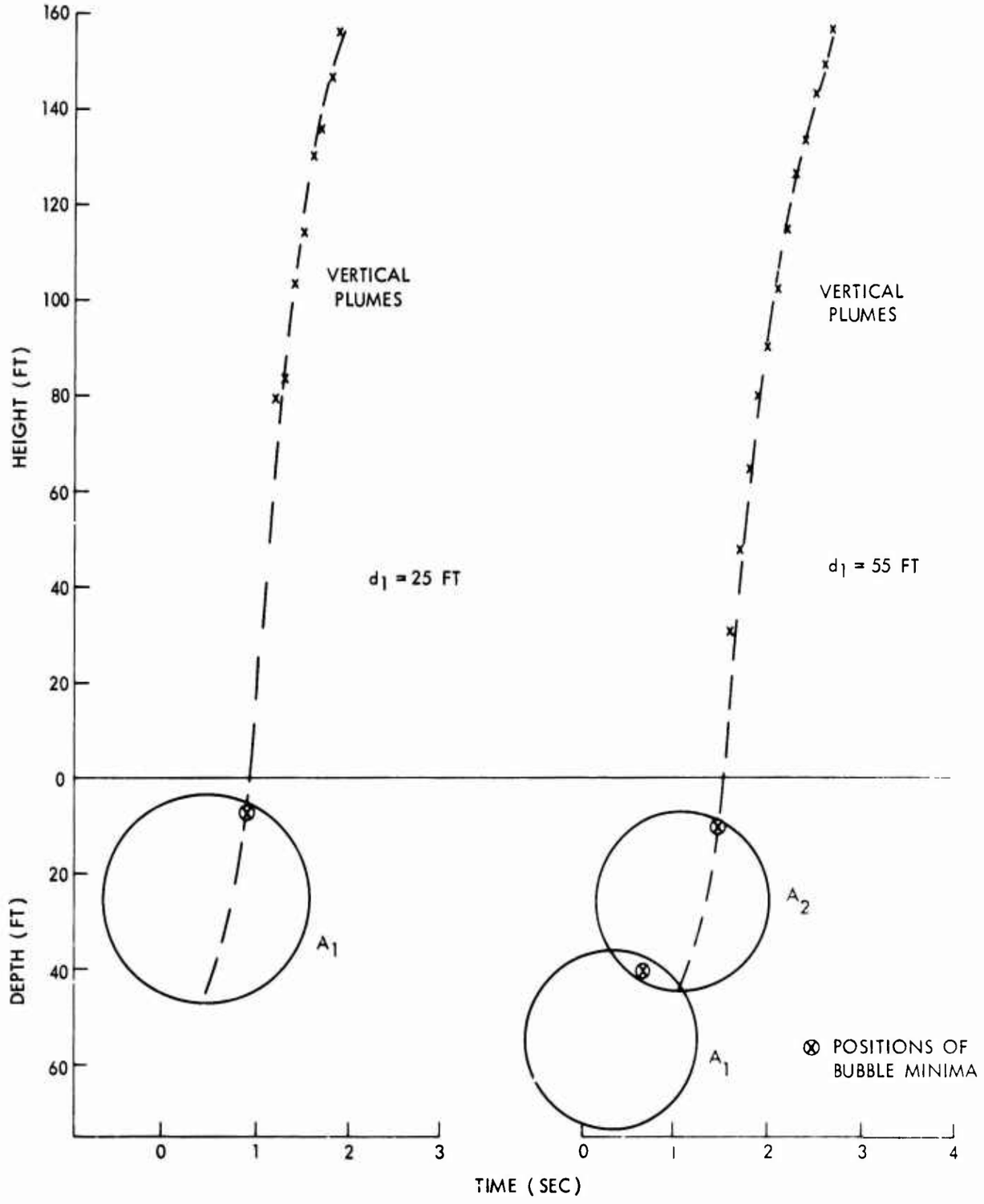

FIG. 9 BUBBLE MIGRATION AND PLUME RISE FOR DEEP 300-LB EXPLOSIONS

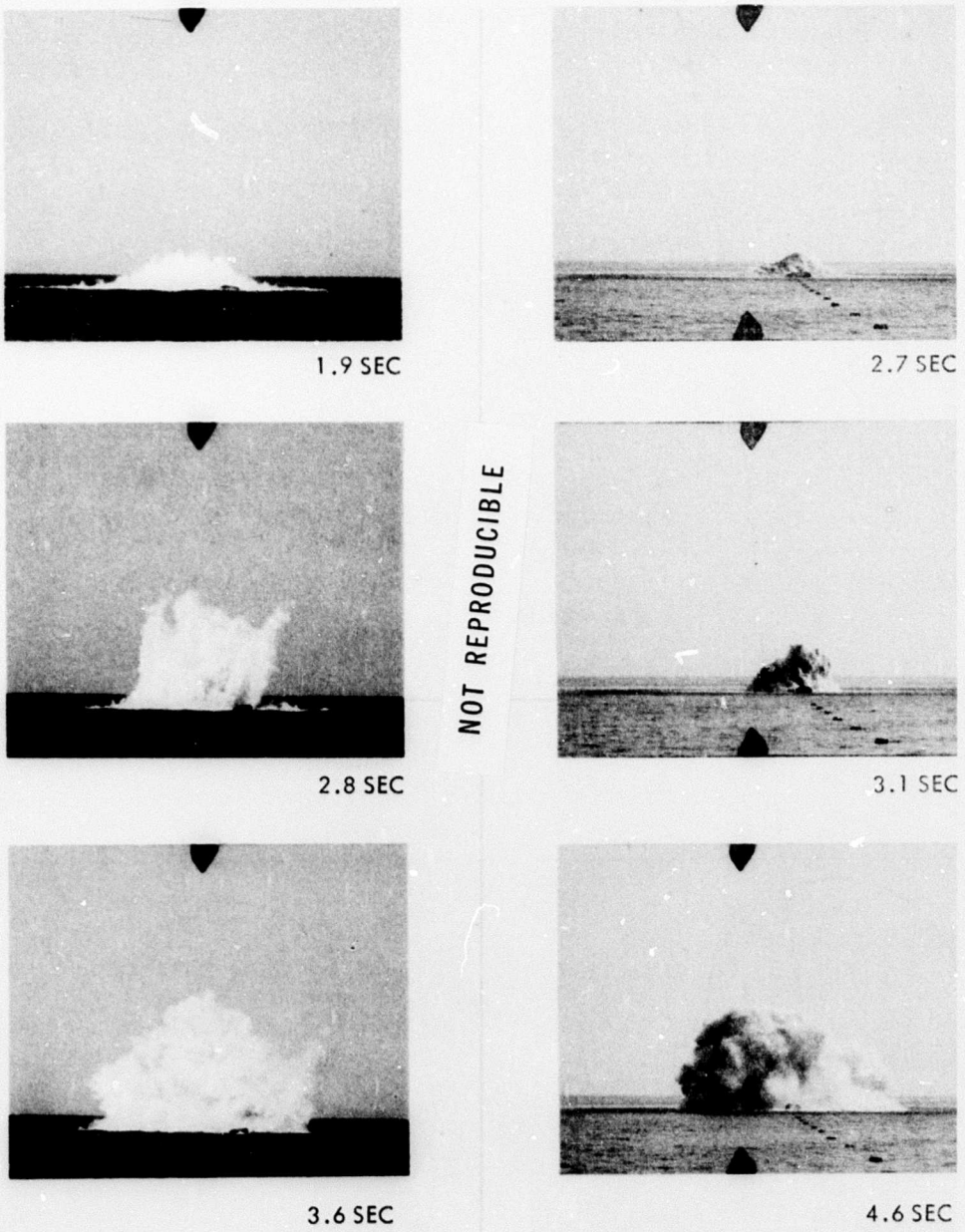

FIG. 10 MOUND AND PLUME FORMATION BY VERY DEEP 300-LB EXPLOSIONS

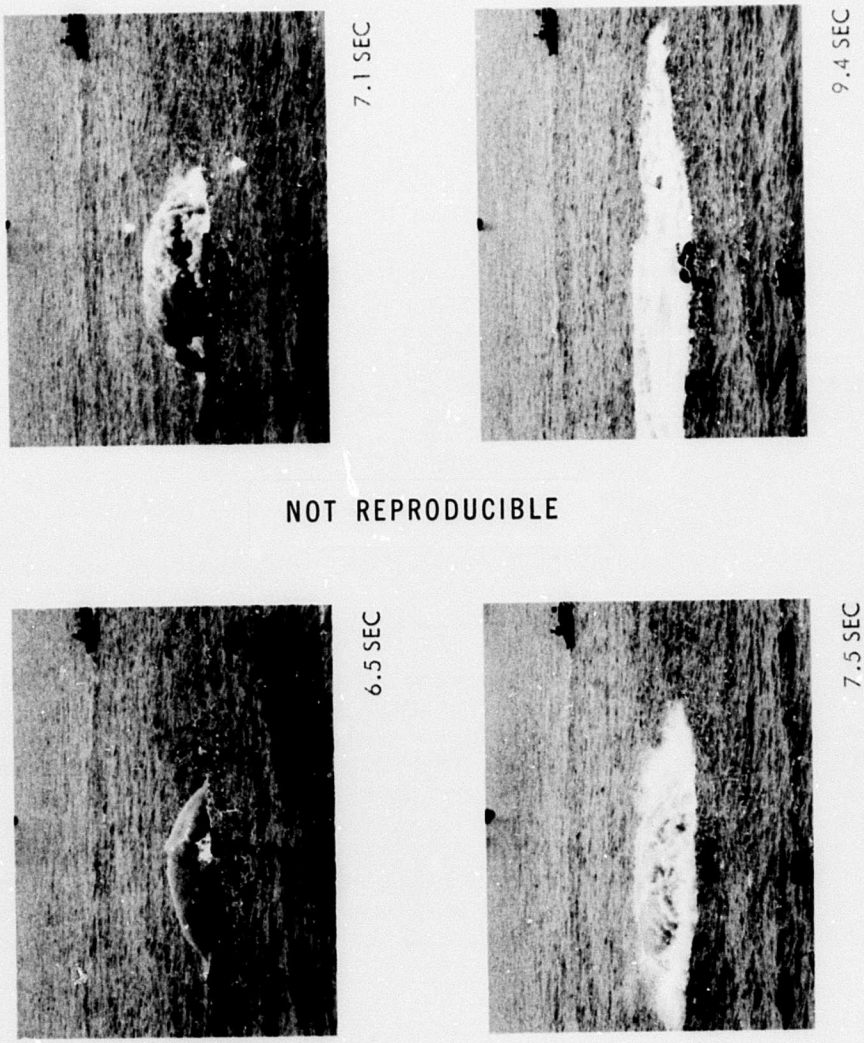

FIG. 11 MOUND DEVELOPMENT AFTER A VERY DEEP 50-LB EXPLOSION

When an explosion produces a column or plumes, these spill over and collapse at the surface. While the plumes are travelling through the air, droplets of water are stripped off at their boundaries by turbulent frictional processes. This leads to the formation of a toroidal aerosol called the base surge. The surge has an initial bulk density appreciably higher than that of a natural cloud, and it spreads out radially. However, as a result of radial expansion and the rainout of large drops, it soon begins to resemble a natural cloud in behavior and appearance (Young, 1965). In the case of 300-pound explosions, the base surge is short-lived and it usually evaporates within about 20 seconds.

In all cases where plumes, mounding, or upwelling occur at the surface, a smooth round patch, or pool, remains after the other phenomena have subsided or have been carried away by the wind. Some of the water in the surface pool doubtless originates from the collapsing plumes, while the remainder is caused by the continued upwelling of water in the wake of the rising bubble. When the only surface manifestation is an upwelling, the pool is probably simpler in structure.

The scaling of explosion bubble and surface phenomena is relatively complex. This was discussed in somewhat abbreviated form by Cole (1948), and a more thorough description of the principles and methods of scaling of all underwater explosion phenomena was published by Snay in 1961. For current purposes, it is adequate, and within the range of accuracy of the data and the requirements of the problems under consideration, simply to reduce the phenomenology data in terms of geometric scaling of the first maximum bubble size for explosions at all depths. This has been done to separate the different types of observed surface phenomena in Figure (12).

It should be pointed out that the field test data utilized as a basis for Figure (12) did not extend to the depth of upwelling. There is no clear evidence of the depth required to achieve this effect for large free-water shots. However, photographs of bubble behavior in the NOL accelerated tank indicate that a value of d_1/A_1 of about 25 is reasonable for the transition from mounding to upwelling, and this result was utilized in the preparation of the figure.

Some indication of the possible containment depth for a conventional explosion was obtained from the records of three of the CHASE shots. These were part of a series conducted for the purpose of disposing of large quantities of surplus and obsolete munitions. In the three shots of interest, the munitions were loaded on cargo vessels which were armed for underwater detonation and were scuttled. As the explosives were of various compositions, were cased in different types of mines and bombs, and were loaded in different holds of the ships, it is difficult to establish an effective charge weight in each case, though, in principle, this can be done by measuring the shock wave and the bubble period. In practice, experimental difficulties were encountered in every case, and the assigned values were only rough estimates.

The behavior of the bubble from an explosion of this type is also uncertain, as the diameter of the bubble at its first maximum would be comparable to the size of the ship. It would be expected that the bubble would be distorted and partially broken up during the first pulsation by the presence of the debris from the ship, and that the upward migration might be retarded. Nevertheless, the CHASE events are the largest conventional underwater explosions on record and, as such, have some value for present purposes.

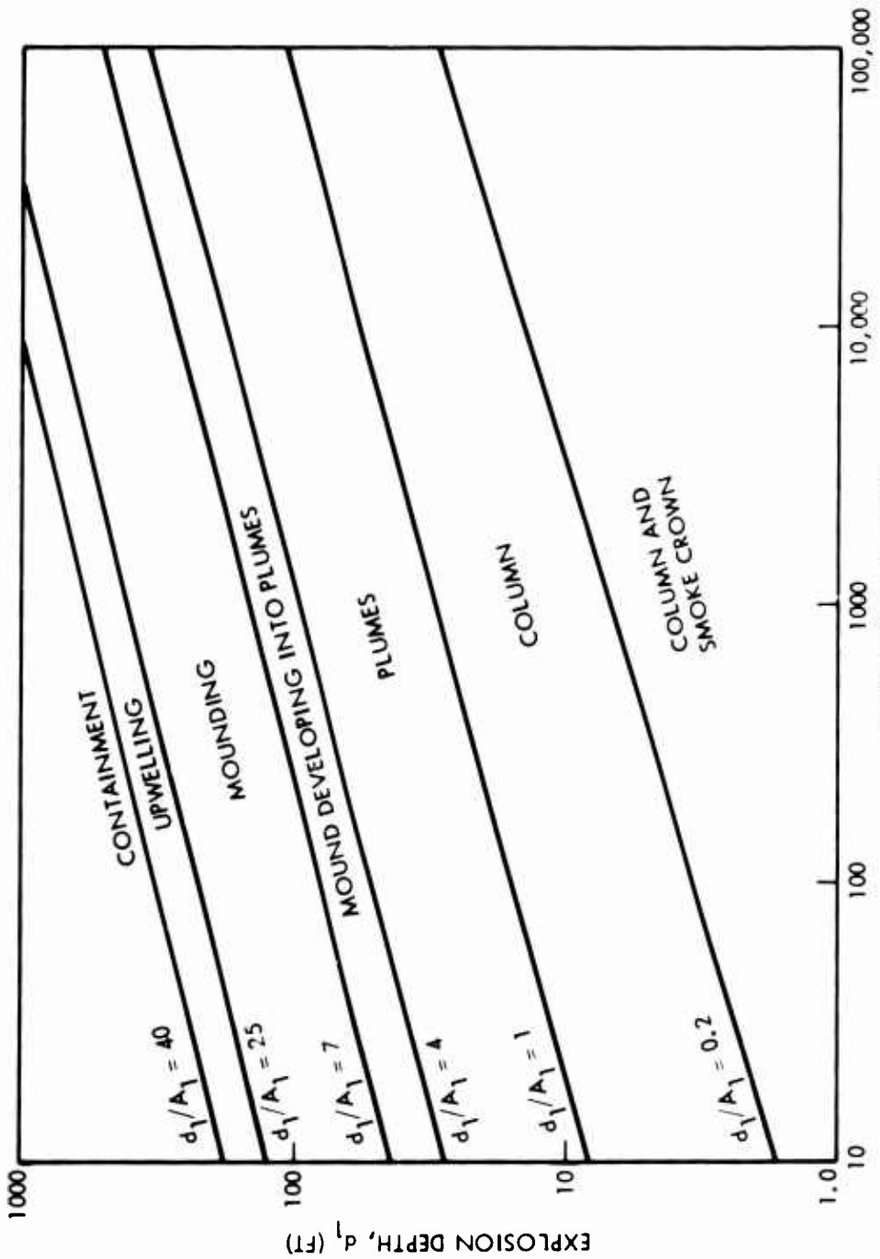

FIG. 12 SURFACE EFFECTS OF CONVENTIONAL FREE-WATER EXPLOSIONS

The shots of interest are listed in Table 1, with the best estimates of the important parameters (Sherman 1971):

TABLE 1

CHASE SHOT DATA

Shot No.	Weight (TNT Equivalent) (tons)	Depth of Burst, d_1 (ft)	Maximum Bubble Radius, A_1 (ft)	d_1/A_1	Surface Phenomena
III	700	900	144	6.25	Mound-Plumes
IV	310	895	110	8.14	Mound
V	1000	3750	102	36.8	None

As the phenomena of Shots III and IV were consistent with those of free-water explosions in controlled experiments it may be assumed that Shot V also behaved in a consistent manner. The situation is not clear, however, as the explosion occurred at night. A fluorescent dye tracer had been placed in the scuttled vessel, and a thorough search was conducted for a surface pool by means of infrared scanning by an aircraft and a fluorometric survey by a ship. No evidence of a surface pool was found, although dye was detected beneath the surface. (These results were included in a classified report by Kaulum and Olson.)

In view of the circumstances, and the expectation that an unimpeded free-water explosion bubble would probably migrate further before breaking up, it seems reasonable to utilize a depth of 40 maximum bubble radii as an estimated containment depth, rather than the CHASE V value of 36.8.

On this basis, it is possible to predict the nature of the surface effects of underwater explosions, though not the dimensions and times of arrival. The time, however, is unimportant in regard to environmental effects, as it is less than one minute in almost all cases except for explosions near the containment depth. Information concerning the dimensions of the surface phenomena of shallow and very shallow explosions has been given by Milligan and Young (1954) and by Young (1965), and the measurements of the surface phenomena of deep and very deep explosions were summarized in a classified report by Young. Figure (13) presents plume height data from these sources in reduced dimensions. As the figure shows, plume heights are not very reproducible, but the dashed curve is a possible upper limit for all but a small percentage of explosions.

Plume heights and surface pool radii are the most important dimensions for the establishment of the maximum extent of explosion products at early times. Very few measurements of surface pools have been made, but a method of estimating the maximum extent is given in Section V.

To predict the nature of the surface effects governed by the initial bubble geometry for TNT and Pentolite, the parameter d_1/A_1 may be calculated from the depth of explosion and the value of A_1 obtained from Equation 1. If another explosive is used, the radius coefficient in Equation 1 may differ. In general, the coefficients are larger for military explosives, and almost all are classified.

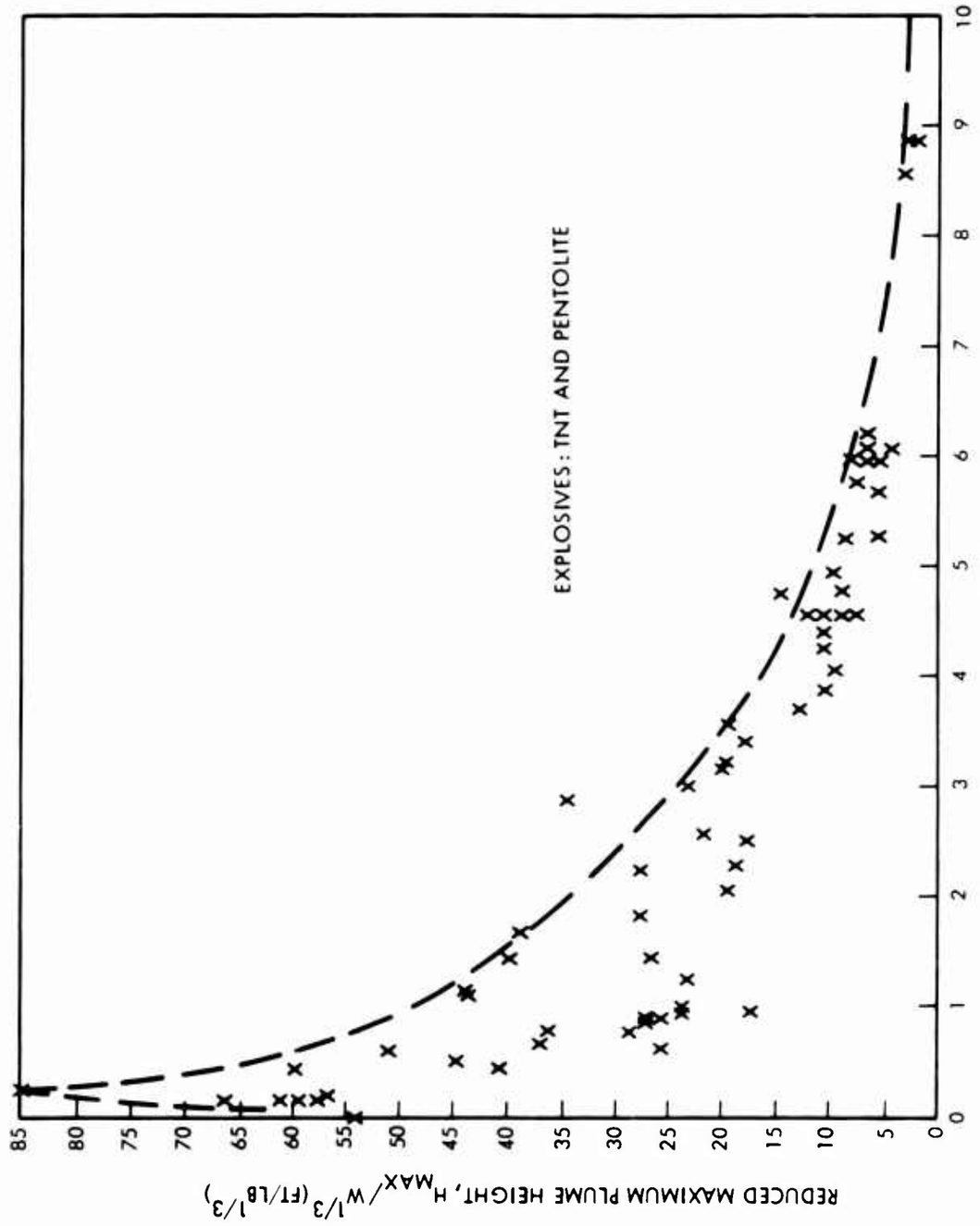

FIG. 13 PLUME HEIGHT DATA

In the case of shock wave effects, a different approach is needed. For example, the peak pressure in the shock wave from an underwater Pentolite explosion is slightly higher than the peak pressure from a TNT explosion of the same weight (Figure 1). It may be stated in this case that 1.00 pound of Pentolite is the equivalent of 1.11 pound of TNT. For most other explosives, a classified NOL publication by Holland may be referred to.

IV TRANSFER OF HEAT FROM THE BUBBLE TO THE ENVIRONMENT

When an explosion takes place, the temperature of the products may be initially of the order of 3000 K (Cole, 1948). It might therefore be expected that heat would be transferred to the surrounding medium by radiation and conduction. However, a few order-of-magnitude estimates are sufficient to demonstrate that these processes can be neglected.

For example, if a charge radiates in the manner of a black body at a temperature of 3000 K, the heat flux density, according to the Stefan-Boltzmann law, is 110 cal/cm^2 sec. A spherical one-pound charge of a conventional explosive, such as TNT, has a surface area of about 210 cm^2. The radiated energy flux is therefore 23,000 cal/sec. However, as the high temperature persists for only about one millisecond, the energy radiated at this rate is about 23 cal. Subsequent radiation is less and is doubtless negligible.

Although sea water is relatively transparent to visible light, the extinction coefficients for infrared radiation in water are high. For example, at a wave length of 1.3 microns, 99.5 percent of the radiation is absorbed in a layer 5.3 cm thick, and, at a wave length of 1.4 microns, the same percentage absorption occurs in a layer 0.53 cm thick (Dietrich, 1957). Consequently, any heating by radiation would be confined to a very thin layer.

In the case of heat conduction, which would be a molecular process in this situation, a similar conclusion may be reached. The thermal conductivity of sea water was reported by Nukiyama and Yoshizawa (1934) to be 0.00135 cal/cm sec C at a temperature of 10 C. If phase changes are neglected and the assumption is made that a temperature gradient as great as 1000 C/cm exists in a thermal boundary layer adjacent to a one-pound TNT charge, the heat flux is calculated to be only about 280 cal/sec. This lasts for a period of about one millisecond.

It seems evident, then, that shock wave heating would be the only process of significance adjacent to the charge. This process would be brief in relation to the time scale of bubble phenomena, but the heated layer should remain in position through most of the first bubble pulsation.

When the bubble grows in size, its temperature drops rapidly as a result of adiabatic expansion, and the strength and direction of the temperature gradients at the bubble interface should change accordingly. When a bubble is fully expanded, the internal temperature might be less than the water temperature, which would lead to a flow of heat into the bubble. At the same time, the bubble pressure is below the hydrostatic pressure of the environment, and evaporation could occur at the bubble wall because of the vapor pressure excess in the water. If evaporation takes place, a certain amount of latent heat will be transferred to the bubble in the process, though, since the flux of heat and vapor into the bubble are molecular processes, it appears certain that this effect can be neglected because of the short time available.

On the other hand, if the pressure within the bubble drops below one atmosphere, the water at the interface will boil at a temperature less than 100 C. Figure (14) shows the calculated values of the pressure (P_{min}) in fully expanded TNT and Pentolite bubbles as a function of the hydrostatic pressure at the depth of burst, and also shows the temperature of boiling at these pressures. For these explosives, the pressure in the bubble drops to one atmosphere when an explosion occurs at a depth of about 350 feet and to less than one atmosphere at shallower depths.

As a consequence of the variation of P_{min} with explosion depth, the amount of steam formed at the bubble interface will be a function of depth. In addition, more steam would be expected from Pentolite than from TNT, because of the greater shock wave heating by the former. However, the layer of water hot enough to boil is very thin when the bubble is fully expanded, and it is doubtful that the effect has significance.

Interfacial boiling has been observed in laboratory-scale model tests when the air pressure in a tank was reduced to less than one-tenth of an atmosphere and the ambient water temperature was relatively high (Taylor and Davies, 1943; Snay 1964). The rate of boiling was rapid enough to affect the maximum and minimum bubble radii, and it was clear that the vaporized water did not all recondense when the bubble collapsed. Consequently, there was a net increase in the mass of the bubble (Snay 1964). This phenomenon differed from shock wave heating, however, as all the surrounding water was at a high temperature, and not just the water in a thin shell.

Perhaps the best evidence that the transfer of heat between an explosion bubble and its environment is negligible prior to the bubble collapse is the fact that theories based on the assumption of adiabatic behavior of the bubble gases have given accurate results when used for the calculation of bubble phenomena.

The experimental data available on the temperature changes produced in water by underwater explosions were summarized in a classified report by Young and Scott. Virtually all of these data were acquired on experiments conducted with a steam-generating explosive called Lithanol, which was developed for the specific purpose of modelling some of the bubble phenomena of underwater nuclear explosions (Murphy, 1963). However, in the first Lithanol series, a few parallel tests were conducted with Pentolite, and the effects of the gas and steam bubbles were compared.

When very deep Lithanol explosion tests were conducted at a depth equal to eight bubble radii or more, the surface phenomena were smaller in size than on comparable Pentolite tests, because the steam in the Lithanol bubbles had condensed while the bubbles were migrating toward the surface. Because of the condensation of steam, which takes place mainly at the times of bubble collapse, the Lithanol bubbles lose energy more rapidly than explosion bubbles containing permanent gases. Consequently, the products mix more rapidly with the surrounding water, and heating of the water by the mixing process is relatively fast. It would therefore be expected that a Lithanol bubble would transfer its heat to the environment more rapidly than a gas bubble of the same size from a conventional explosion at the same depth.

To monitor the temperature changes produced by the upwelling of water from the explosions, glass-bulb thermistors were mounted on floats in the

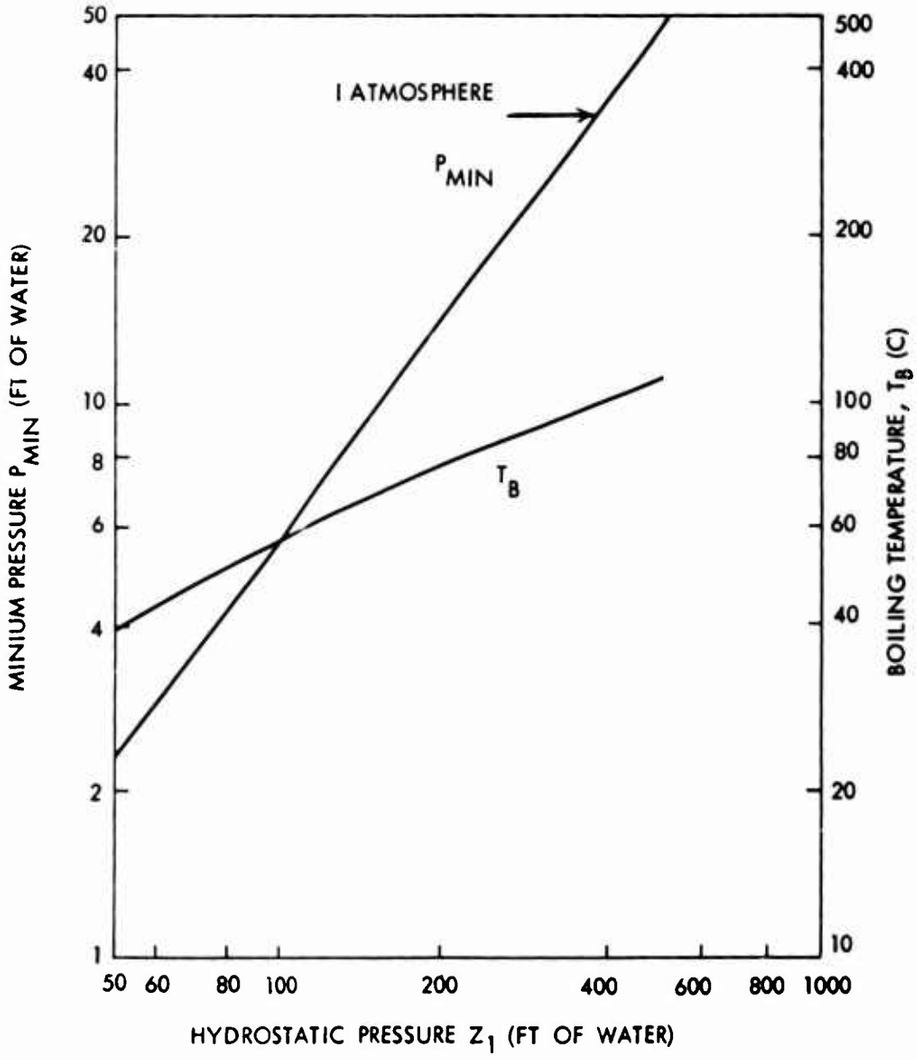

FIG. 14 PRESSURE AND BOILING TEMPERATURE IN FULLY EXPANDED TNT AND PENTOLITE BUBBLES

vicinity of surface zero. In most cases, these were at a depth of one foot, but on a few tests, the thermistors were at depths extending to 30 feet. In general, the gages were not placed closer than $15W^{1/3}$ feet to an explosion, because of the possibility of damage by the shock wave. Records were obtained by this means from 45 Lithanol tests. In addition, temperature data were obtained by traversing the surface pool in a boat with a thermistor held one foot beneath the surface. This procedure was followed on 43 tests.

In general, the maximum difference between the ambient water temperature and the temperature in the water upwelling from the explosion was small. The overall average of maximum temperature changes from free-water Lithanol explosions was 0.42 C (based on 109 observations), and the largest change recorded was 1.86 C. These changes were both positive and negative. In almost every case, temperature stratification was present in the water. This was most pronounced during a series conducted in the Chesapeake Bay during the summer months when the surface layer was often 3.0 C warmer then the bottom layer. It was found that the temperature changes at the surface were closely correlated with the ambient temperature profile, i.e., if an explosion occurred in a cool stratum of water, a relatively cool upwelling followed at the surface. It was concluded, on this basis, that any heating of the water by the explosions was of a smaller magnitude than the natural temperature effects, and could, at most, be of the order of a few tenths of a degree C.

This result was verified by firing shots in isothermal water. Two Lithanol tests were conducted in the Patuxent River during 1965 at a depth slightly greater than one bubble radius. As the bubbles collapsed just beneath the surface, it was expected that any heating by the explosion would be confined to relatively shallow surface pools. When these pools were traversed by a boat about 20 seconds later, the greatest observed rise in temperature was 0.07 C.

In addition, data were obtained from three very deep explosions in isothermal water near Panama City, Florida in 1969. These showed definite evidence of heating, but the maximum change recorded was only 0.37 C.

The general conclusion reached as a result of the Lithanol tests was that the heat produced by the explosions was dissipated rapidly by turbulent mixing and that the temperature changes resulting from this process were only a few tenths of a degree C. Greater changes were observed when the rising mixture of water and explosion products entrained sub-surface water and carried it to the surface.

As a gas bubble mixes with the environmental water at a slower rate, even less heating would be expected. Temperatures were recorded on only two 15-pound Pentolite tests, which is clearly insufficient to check this point. The data are presented in Figures (15) and (16), together with the temperature-depth profile of the environment. The shots were both at a 70-foot depth, but 907 (Figure 15) was in free water and 901 (Figure 16) was on the bottom. On Shot 907, a maximum temperature increase of 0.17 C was recorded at the surface, while, on Shot 901, a temperature decrease of 0.31 C was recorded. In the case of Shot 907, the water temperature was 0.8 C higher at the depth of the explosion than at the surface, and, on Shot 901, the water temperature was 2.3 C colder at the bottom than at the surface.

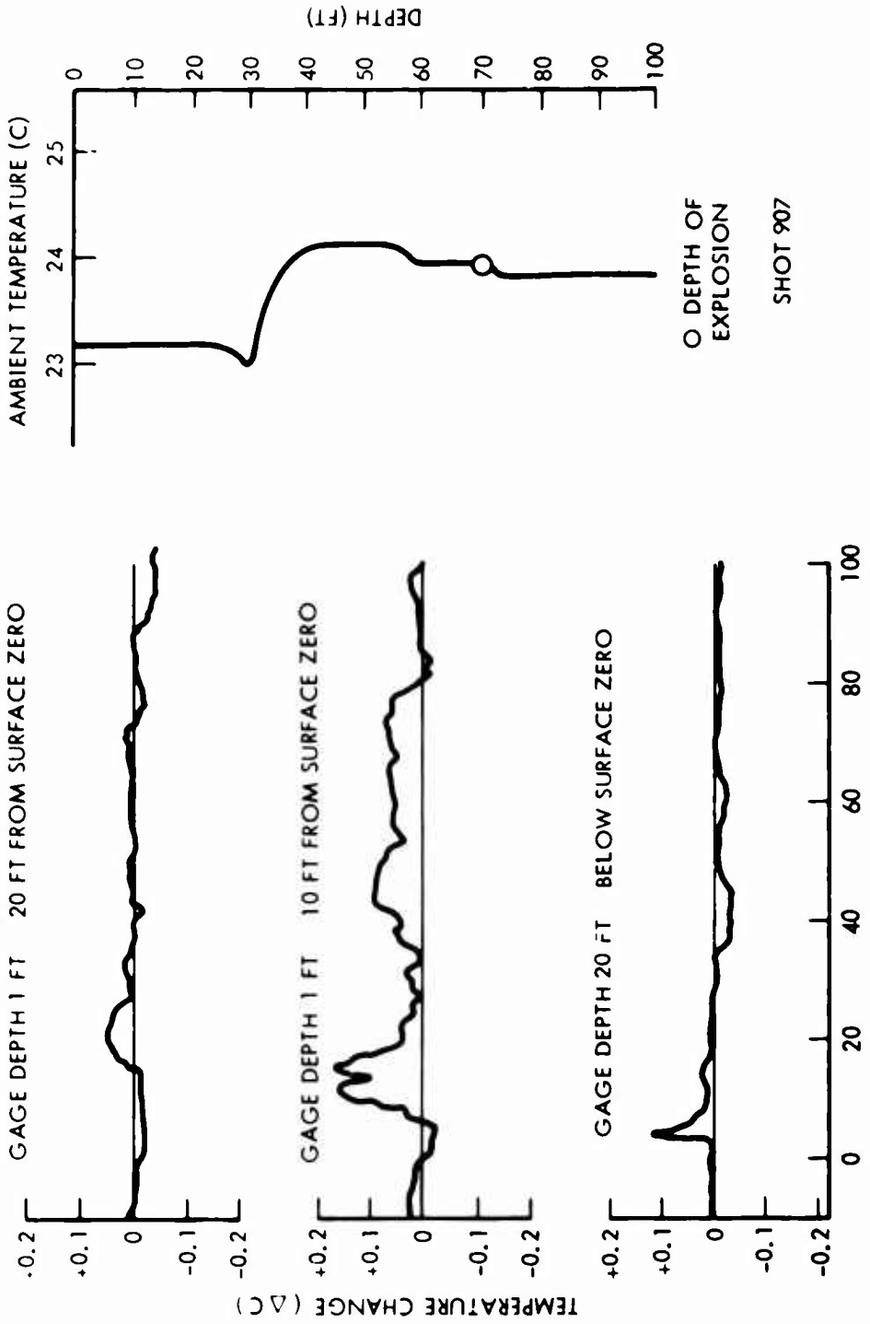

FIG. 15 TEMPERATURE CHANGES PRODUCED BY A PENTOLITE EXPLOSION IN FREE WATER

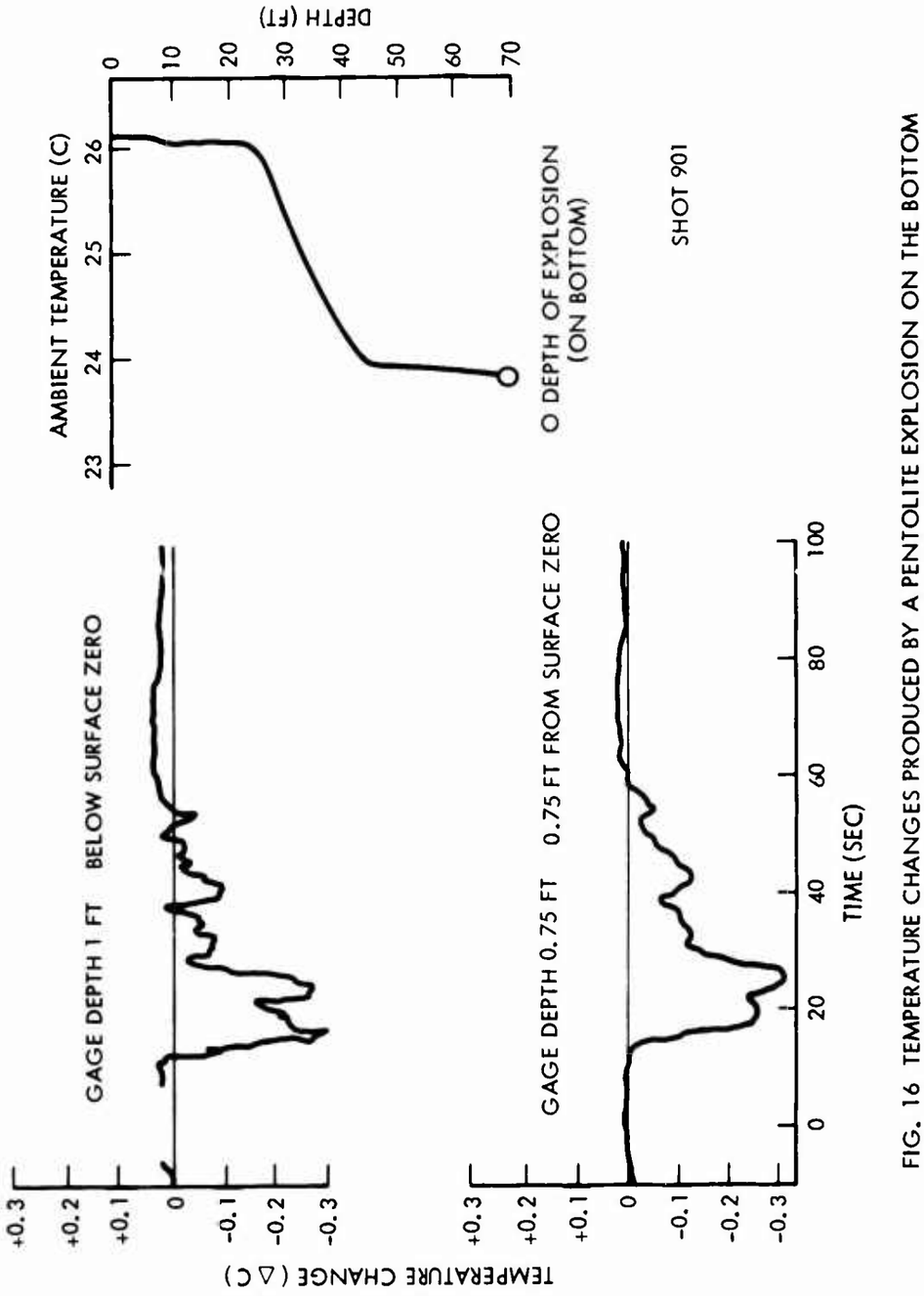

FIG. 16 TEMPERATURE CHANGES PRODUCED BY A PENTOLITE EXPLOSION ON THE BOTTOM

The Pentolite data are consistent with the Lithanol measurements, in that there is no evidence of appreciable heating of the water by the explosions. If significant heating did occur, i.e., in the vicinity of the explosions, turbulent mixing of the heated and ambient water reduced the temperature contrast to a negligible level within a few seconds. On both shots, the surface temperature returned to the ambient value in less than one minute.

Although the pertinent data are limited, these results, combined with a general understanding of the behavior of explosion bubbles, indicate that the net heating of water by explosions is so brief and so limited in magnitude that it can be completely ignored in regard to effects on the environment.

V MIXING OF EXPLOSION PRODUCTS WITH WATER

A considerable amount of knowledge has been acquired concerning the chemistry of explosives and the shock wave and bubble phenomena of underwater explosions, but only limited attention has been given to the dispersion of the explosion products after the detonation takes place. The ultimate disposition, of course, depends on whether the product is gaseous or a solid, and whether it is readily soluble in water or remains in a particulate form.

As there is an extensive literature on explosion chemistry, this subject will not be discussed in detail here. As pointed out by Cole (1948), Christian and Snay (1951), Price (1959), and Zeldovich and Kompaneets (1960), the most widely used explosives consist of compounds of carbon, hydrogen, oxygen, and nitrogen (TNT and Pentolite are examples of these). The basic reaction products are N_2, H_2O, CO_2, CO and H_2. In the case of TNT, however, an insufficiency of oxygen exists, and free carbon is formed. Aluminum is frequently incorporated into explosives (e.g., HBX-1), resulting in the formation of aluminum oxide particles. Explosives such as TNT and HBX-1 can be handled safely in large quantities, but Pentolite is generally not used in charges weighing more than 300 pounds.

Explosives of a different nature are used in very small quantities as detonators, generally less than one gram in weight. These include compounds such as lead azide and mercury fulminate.

Previous experiments related to the deposition of explosion products in water by underwater explosions have been directed toward the prediction of the history of the radioactive fission products of underwater nuclear explosions. However, as these tests were usually conducted with chemical explosives, some of the results are also applicable to the environmental effects of current interest. In most cases, it was decided beforehand that more precise data could be obtained by using a chemical or radioactive tracer in the charge than by the analysis of water samples for the actual explosion products. In addition, the emphasis was often on the deposition of products, or tracer, in the air, with less attention given to the percentage remaining in the water.

An early effort along these lines was the incorporation of about 1090 pounds of lithium chloride and about 1860 pounds of cobalt chloride into a 45-ton explosive charge of TNT (Young, 1954). As this was a very shallow explosion ($d_1/A_1 = 0.07$), a high percentage of explosion debris was ejected to the air. Much of this dropped back as liquid fallout with entrained explosion products and tracer. Samples of the fallout and base surge were analyzed chemically, but no

sampling of the pool was done. Only preliminary results were published, and the data were never interpreted. However, the utility of the technique of utilizing chemical tracers in conventional explosives was demonstrated.

A more extensive program with similar objectives was the HYDRA IIA series, consisting of thirteen 10,000-pound HBX-1* charges, fired in deep water at depths ranging from 6.6 feet to 140 feet. Radioactive tracers and dyes were employed to follow the history of the explosion products. The data are useful for the evaluation of environmental effects, and pertinent results will be summarized here as given in a classified report by Shirasawa and Gurney.

The radioactive tracers used on HYDRA IIA were Lutetium-117 and Xenon-133, the first in a particulate form and the second a gas. Although these were employed on four shots, detailed data were acquired on only two. Shot 12 was fired at a depth of 15.4 feet ($d_1/A_1 = 0.181$) with the Lutetium tracer in the form of Lu_2O_3. As the test was in the very shallow range, a column, smoke crown, and base surge were formed, and a large surface pool remained after the surface effects had subsided. The pool was distorted considerably by the 0.6 knot current.

It was found that the Lutetium had become associated with particles of aluminum oxide, a product of the explosion. These particles had an average diameter of 250 microns. It was concluded that the tracer distribution in the sea was probably determined to a certain extent by the rate of settling of particles and not entirely by mixing processes. About 42 percent of the Lutetium was found in the pool, and it seems likely that a sizable portion of the remainder settled to the bottom.

The Xenon-133 tracer was used on Shot 13, which was only slightly deeper, at a depth of 17.0 feet ($d_1/A_1 = 0.202$). The column and crown were white, although some blackness was observed in the previous test. However, the dimensions of the surface phenomena were approximately the same. In this case, no current was observed in the test area, and the pool was circular in shape. Only nine percent of the gaseous tracer was found in the pool, and it was assumed that the remainder had escaped into the atmosphere.

After two hours, the pool had become relatively stable, and it was evidently expanding as a result of turbulent diffusion alone. At this time, the radius was about 1450 feet. Vertical soundings were made in the pool, and these showed considerable variability, but at late times the depth of the pool averaged about 40 feet. On this basis, a volume of 260×10^6 cubic feet was calculated.

As the pool was distorted on Shot 12, the measurements of its dimensions are more difficult to interpret. The radial growth, after the initial ten minutes, was more rapid than on Shot 13, and the radius was possibly 2100 feet after two hours had elapsed. The depth data were quite variable, but indicated a possible value of 20 feet when the pool had stabilized. These values imply a pool volume of 280×10^6 cubic feet. This value is not as reliable as the estimate for Shot 12; nevertheless, it is virtually the same, and an average of 270×10^6 cubic feet

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*For HBX-1, the bubble radius coefficient is 14.4. For the conversion of bubble effects, 1.48 pound of TNT is the equivalent of 1.00 pound of HBX-1.

seems to be a reasonable value to use.*

The tracer measurements indicated that the tracers were initially distributed symmetrically in an annular ring, which filled later as a result of upwelling and mixing. At later times, the distribution within the pools was approximately uniform.

The maximum radius of the surface pool is an important quantity for the assessment of the extent of effects on the environment. Unfortunately, this has been measured in only a few cases. As the pool usually becomes indistinguishable from its surroundings while it is still growing rapidly, it is difficult to estimate the maximum extent on the basis of photography alone. The maximum pool radii reported for HYDRA IIA Shots 12 and 13 were based mainly on measurements of radioactivity in the water, although, in the case of Shot 13, the maximum value was verified by a transit sighting of the dyed pool.

Figure (17) presents the available data on the maximum radii of surface pools as observed visually and in photographs. The data exhibit a good cube root relationship, although the values of d_1/A_1 for these shots range from 0.181 to 23.8. It might be expected that the maximum pool size would decrease with increasing depth of explosion because of the loss of energy of the bubble as it migrates upward, and this probably occurs to some degree. However, a passive bubble does not slow down continually, but reaches a terminal velocity proportional to the square root of the radius (Taylor and Davies, 1944). In addition, a bubble might expand because of the reduced hydrostatic pressure as it approaches the surface (e.g., LeBlond, 1960), leading to an increase in velocity. In view of these factors, and the scatter of the measurements, it seems reasonable to use the relationship given for all shots to a depth of 25 bubble radii, with an assumed error of at least 20 percent.

Although the cube root relation shown in Figure (17) is based on only limited data, it is interesting to note that the equation gives almost exact agreement with the maximum radius (measured photographically) of the pool formed by a nuclear test at a depth slightly in excess of one bubble radius. This provides good evidence that the cube root relationship is realistic.

The 1450-foot radius determined for HYDRA IIA Shot 13 is about three times as large as that given by the equation based on visual or photographic techniques. The larger value was obtained at two hours, while the measurements obtained from shots of the same weight were generally obtained between 30 and 40 seconds after zero time. In the absence of other information, it may be assumed, therefore, that the true maximum pool radii for all underwater explosions are three times as large as those observed by conventional means. Using the actual value for Shot 13, and a TNT conversion factor (10,000 lb HBX-1 = 14,800 lb TNT); this results in the following equation:

*It is interesting to note that if all the heat of the explosion (6.8×10^9 calories) were utilized to heat this volume of water uniformly, the temperature increase would be only 0.001 C, which is clearly negligible. This is consistent with the conclusions reached in Section IV, as the time of measurement of this volume was about two hours after the time of explosion.

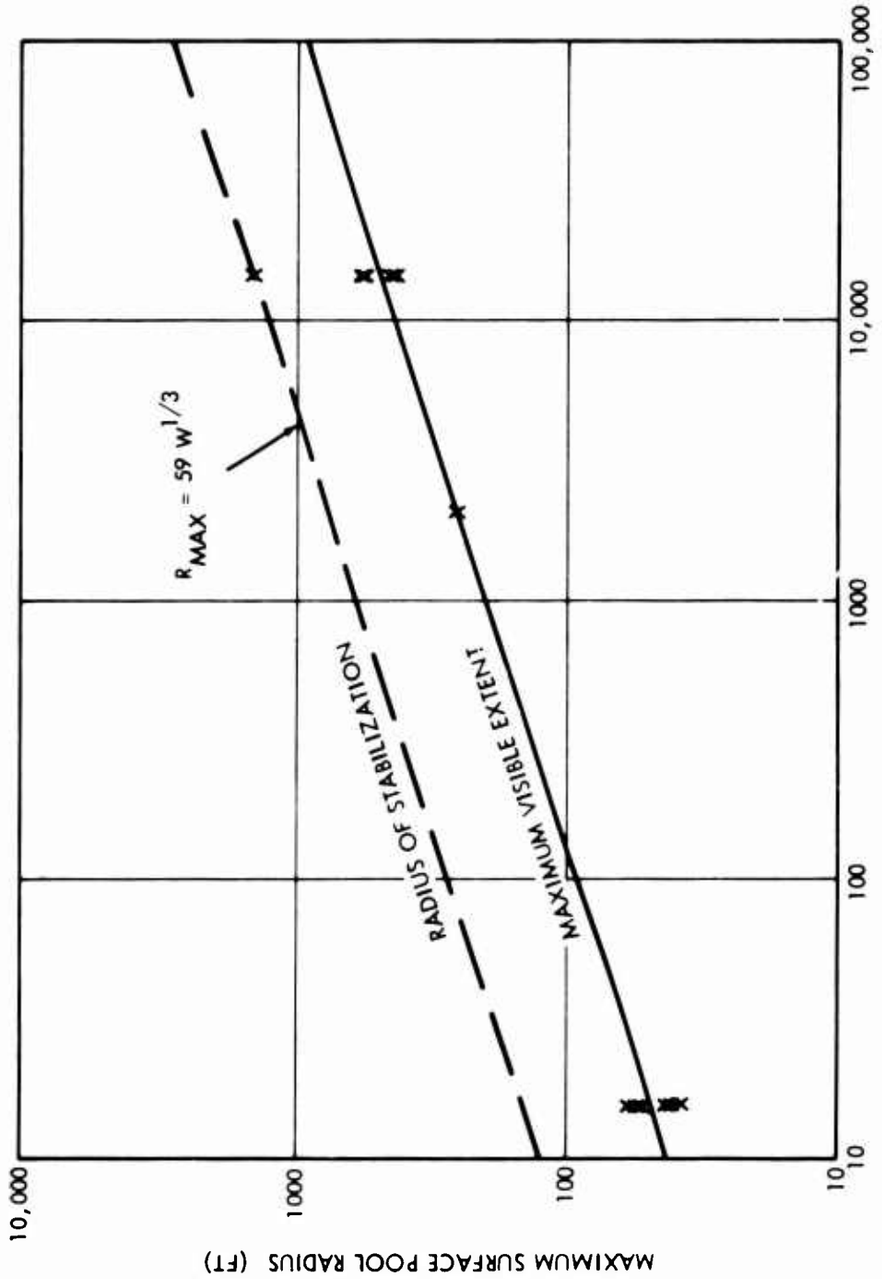

FIG. 17 MAXIMUM RADIUS OF SURFACE POOL VS CHARGE WEIGHT

$$R_{max} = 59\ W^{1/3} \quad , \tag{4}$$

where: R_{max} = radius of the surface pool when the energy of the explosion has been dissipated, ft.

As the pool volume should be proportional to the charge weight, the average volume of Shots 12 and 13 can be used to formulate the following equation for TNT explosions:

$$V_{max} = 18{,}000\ W \quad , \tag{5}$$

where: V_{max} = stabilized volume of the surface pool, ft^3.

Assuming the validity of Equations 4 and 5, and a cylindrical shape, the pool depth at the time of stabilization may be estimated from the following:

$$h_{max} = 1.6\ W^{1/3} \quad , \tag{6}$$

where: h_{max} = depth of the surface pool at the time of stabilization, ft.

The accuracy of Equations 4, 5, and 6 is unknown, and it is highly speculative to assume that they are valid for all underwater explosions at depths less than 25 maximum bubble radii. However, they are presented here to provide rough estimates of the possible volume and extent of the surface deposit of explosion products in the absence of currents or other oceanographic influences. If additional data become available in the future, it is quite possible that these preliminary equations will have to be modified.

Subsequent to the HYDRA program, Lithanol tests were conducted with fluorescein dye inserted in the charges to serve as a visual tracer of the explosion products. In a later series, conducted with charges weighing 1400 and 13,000 pounds, quantitative measurements of the concentration of dye and lithium (an explosion product) were made in the surface pools. On one test, Xenon-133 was used as a tracer, and the rate of transfer of the gas across the air-water interface was measured.

On three shots, the concentrations of lithium and dye in water samples taken in the pools were found to be closely correlated (correlation coefficients of 0.80, 0.99, and 0.82), indicating that the dye was well mixed with the explosion products. It was evident that some of the dye placed within the charges was decomposed by the explosions, but the experiments showed that dye suspended in a container directly above the charges was equally satisfactory as a tracer.

The data exhibited considerable scatter, but gave some indication of a Gaussian distribution of explosion products in the pools during the period of measurement (4 to 18 minutes after 1400-pound explosion tests).

It can be seen, therefore, that relatively little information is available that is directly related to the deposit of explosion products in the environment. A highly qualitative description can be developed, however, that may serve to establish reasonable limits concerning the magnitudes of interest.

It is obvious that the distribution of products in the air and water will depend on the depth of an explosion and the nature of the products. The total

depth of water is also an important variable if an explosion is within one bubble radius of the bottom, and, in this case, the nature of the bottom is important. The free-water environment is simpler and will be considered first.

Photographic evidence (e.g., Milligan and Young, 1954) shows that an explosion on the water surface generates a smoke cloud in the air and also results in the ejection of some liquid water from the underlying surface. Gaseous products doubtless escape to the atmosphere and some of the smoke remains airborne, but some settles back, probably mixed with water. A pool of water (black in the case of TNT) remains at the surface.

When a charge is at least one-quarter submerged, there is an appreciable reduction in the amount of dry smoke produced, and most of the airborne cloud appears to be water mixed with carbon. Most of this falls back to the surface in a short time. From depths of 0.05 to 0.20 maximum bubble radii, a well developed black smoke crown is visible, and the fallout is even more rapid. At a depth of possibly 0.25 A_1 the column and central jet are white, and it seems that particulate solids either remain in the water or return to it almost immediately at this depth and at greater depths.

It seems reasonable to assume that all of the gaseous products will escape to the atmosphere if an explosion occurs at a depth less than one maximum bubble radius. If a bubble goes through at least one pulsation, sufficient turbulent mixing should occur to remove a fraction of all products from the inside of the bubble. It is not clear what this depth is, but the above-surface observations show that bubble jetting occurs if a bubble is in the deep category. If the explosion is within four maximum bubble radii of the surface, the upward migration is probably strong enough to transport most of the products to the surface, either directly or by means of the vertical current in the wake of the rising bubble.

For deeper shots, it seems evident that some gaseous products will reach the atmosphere if the bubble emerges, either in an active or passive state. In addition, small bubbles that have separated from the explosion bubble at relatively shallow positions will eventually break the surface.

As the first collapse of an explosion bubble is the most energetic, it appears likely that more turbulent mixing of bubble contents with the environment would occur at that time than during the later pulsations. Some ambient water probably enters the bubble and evaporates to become part of the bubble atmosphere, but, at the same time, a portion of the explosion products apparently is deposited in the surrounding water, and is left behind when the bubble migrates upward. This is shown in photographs of small-scale explosion tests in tanks, though the nature of the deposited debris cannot be clearly established. Some of it is probably in the form of tiny bubbles and some of the debris evidently consists of solid particles. A portion of it doubtless originates from the case or coating of the charge. Evidence of debris deposit may be seen at the depths of secondary bubble minima, and a specially heavy deposit is often observed at the depth where the bubble stops pulsating after three or four cycles and converts to a spherical vortex. (See Figures 6 and 7). The depths of the bubble minima may be estimated from graphs published by Snay and Tipton (1962).

During the time a passive bubble migrates toward the surface, explosion products probably leave it at a relatively slow rate as a result of diffusion across the interface and the shedding of small bubbles in the wake. As stated previously,

the main bubble acquires a roughly hemispherical shape when its kinetic energy has been expended. It may break up into a bubble cloud before it reaches the surface.

The mass transfer from gas bubbles rising in liquid has been investigated by chemical engineers and has been found to be a relatively complex phenomenon (e.g., Davies, 1963; Bischoff and Himmelblau, 1968). The rate of transfer is enhanced if bubbles are rising in a stream (Li, et al, 1965) or a swarm (Gal-Or and Hoelscher, 1966). It seems likely that the existing theoretical treatments could be applied to explosion bubbles, as mass transfer coefficients have been determined for most gaseous explosion products.

When the explosion bubble (or bubble swarm) encounters the free surface, the remaining gaseous products probably escape to the atmosphere, but the solid and dissolved constituents become trapped in the surface pool. After the kinetic energy of the vertical and radial motion has been dissipated, the remaining products will probably be in a vertical cylinder extending from the depth of burst to the surface with a diameter equal to $2\ A_1$ and in a broad shallow surface pool. Relatively high concentrations would be expected at the bottom of the cylinder, where the bubble was pulsating, and in the surface pool. Dissolved gases will probably continue to diffuse across the air-sea interface until their concentrations have been reduced to a low level. (This subject was reviewed by Schink, et al, in 1970.)

The concept of a submerged cylinder that increases in volume with increasing depth of explosion may seem inconsistent with the previous assumption of a constant volume of water in the surface pool for all reduced depths to a maximum d_1 of $25\ A_1$. However, the volume of the cylinder represents a region traversed by the rising bubble and its residue. It is always small compared to the volume given by Equation 5.

For example, if a 1000-pound TNT explosion occurs at a depth of 20 maximum bubble radii (d_1 = 348 feet; A_1 = 17.4 feet), the volume of the submerged cylinder is equal to 331,000 cubic feet. The surface pool volume calculated from Equation 5 is equal to 18×10^6 cubic feet. In this case, the cylinder has a volume equal to about 2% of the volume of the surface pool.

Photographs of explosion tests in the NOL accelerated tank show that if the explosion bubble breaks up completely into a swarm of small bubbles, the swarm will expand while rising toward the surface. This effect has not been studied quantitatively, but as a first approximation, the diameter of the submerged cylinder should be increased to $4\ A_1$ for depths in excess of 25 maximum bubble radii.

In regard to the percentage of products deposited, the data from Lithanol and nuclear tests indicate that more than 60% of the products remain in the surface pool if the depth of burst is less than $4\ A_1$. This result should be approximately valid for the solid and dissolved products of conventional explosions.

Without further study, the information summarized here is useful for qualitative guidance only. The following table may be utilized on an interim basis with this limitation in mind. It is consistent with the limited data available, but the accuracy of the values given is unknown. They are assumed to apply to the time of equilibrium, that is, when the turbulent motions in the air and water resulting directly from an explosion have subsided. This can be taken as about $5W^{1/3}$ minutes.

TABLE 2

DEPOSITION OF PRODUCTS OF FREE-WATER EXPLOSIONS

d_1/A_1	Phenomena	PARTICLES AND DISSOLVED SOLIDS			GASES		
		Atmosphere	Surface Pool	Submerged Cylinder	Atmosphere	Surface Pool	Submerged Cylinder
0	Smoke Cloud	100	0	0	100	0	0
0.05	Smoke and Water Cloud	50	50	0	100	0	0
0.20	Large Smoke Crown	10	90	0	100	0	0
0.25	Some Smoke Visible in Column	10	>60	0	100	0	0
1.0	White Column and Plumes	5	>60	0	100	0	0
4	Plumes	2	>60	<38	90	10	0
7	Mound - Plumes	0	>50	<50	>50	<50	<50
25	Mounding	0	>50	<50	>50	<50	<50
40	Upwelling	0	<50	>50	<10	<50	>50
	Containment	0	0	100	0	0	100

All values in percent.

VI BOTTOM SHOTS

An explosion on the seabed leaves a crater that may persist for a considerable period of time. The experimental data are adequate for predicting crater dimensions for TNT explosions on a variety of soils (e.g., Waterways Experiment Station, 1959; Davis and Rooke, 1968); however, very little information is available for water depths in excess of 1.0 $W^{1/3}$ feet. Figures (18) and (19) may be used for estimating radii, depths, and volumes for bottom explosions in clay or sand. Craters probably increase in size with increasing depth of water between 1.0 and 3.0 $W^{1/3}$ feet, and then become smaller at greater depths. However, this has not been quantified because of the lack of data.

No information is available concerning the deposit of explosion products in craters, though it seems likely that some particulate matter would remain after a bottom explosion on any type of sediment. When the explosion bubble expands, the soil is pushed aside and some portion is ejected into the water or air, either in the form of small particles, in the case of sand or mud, or partially in the form of large clumps, if the bottom is a viscous clay. Particulate matter in the bubble might be entrained by, or coalesce with, natural particles at an early stage when they are in close contact. Immediately after the crater is formed (except in clay or rock), water rushes back, smoothes out the lip, and carries some bottom material into the crater, partially filling it. The crater may partially collapse also as a result of lack of cohesive strength. In most cases, crater measurements represent the "apparent crater" remaining after this slumping action occurs.

Generally speaking, the crater radius is a guide to the extent of permanent deformation of the sea floor. As a rule-of-thumb, the bottom is possibly disturbed to a distance of two crater radii. The depth is less meaningful, because it is more strongly affected by slumping, sedimentation, and water flow. The volume is a rough indication of the amount of ejected material. If the water depth is greater than 1.0 $W^{1/3}$ feet, possibly all of this remains in the water, though it may be ejected to the atmosphere for a brief period and then fall back.

Some indication of the persistence of craters is given in a report by Young (1953). Craters formed by 600-pound charges in a viscous clay at Dahlgren, Virginia remained in existence for at least a year, and one crater formed by a 4200-pound charge was measurable three years after the test. Sand craters, however, filled in rapidly.

A knowledge of the properties of the bottom is needed for a thorough evaluation of environmental effects. As marine sediments are frequently classified by the size distribution of their particles, the soil types given in Figures (18) and (19) provide some guidance concerning the possible results of explosions on the bottom. For example, sand particles range from 0.0[illegible] to 2 mm in diameter, and clay particles range from 0.00024 to 0.004 mm in diameter (McAllister, 1970). When dislodged from the seabed, the larger particles fall back rapidly, but the finer particles remain suspended for a period of time as turbid clouds that drift with the current. The rate of fall and the diffusion of sand particles has been studied by Murray (1970). Although clays have small particles, the cohesion between particles often results in greater strength than in the case of sand; consequently, information concerning the mechanical properties of sediments is also needed.

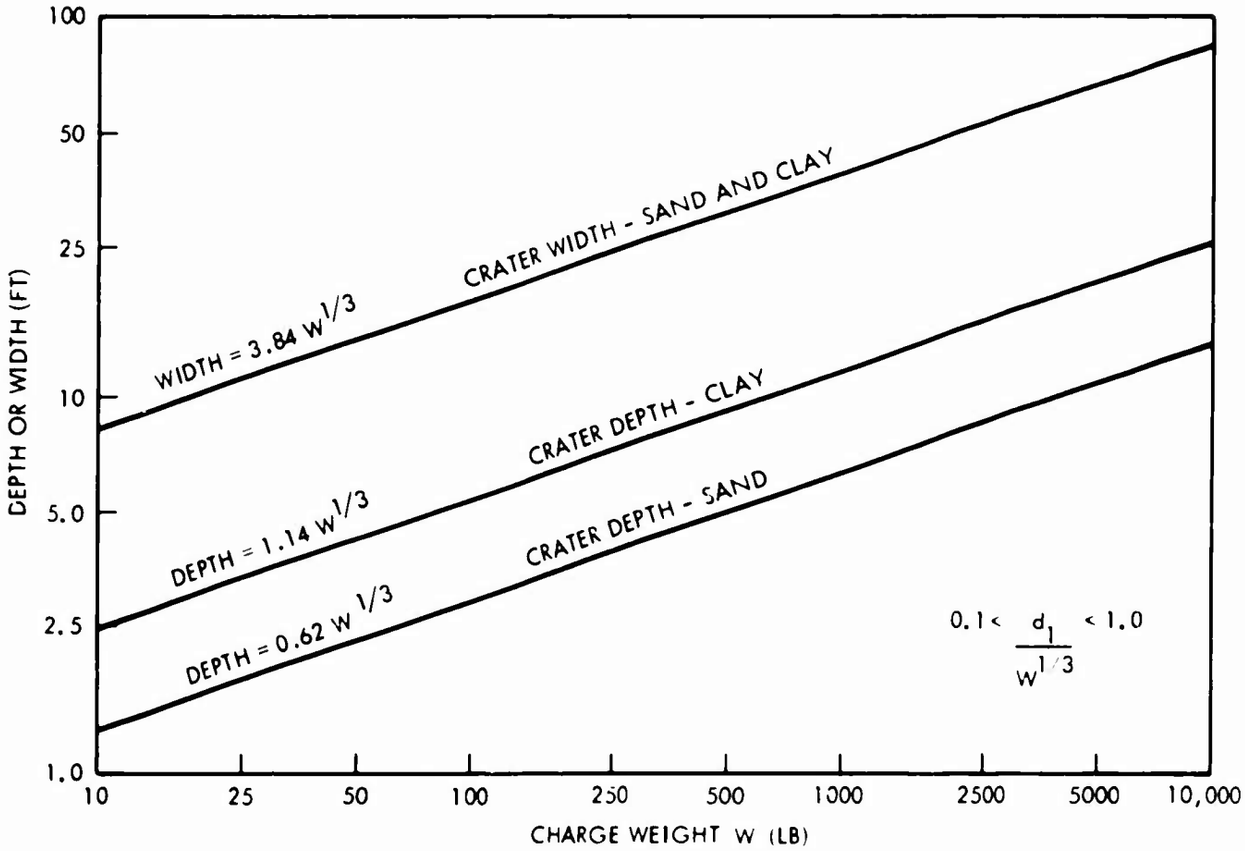

FIG. 18 CRATER WIDTHS AND DEPTHS

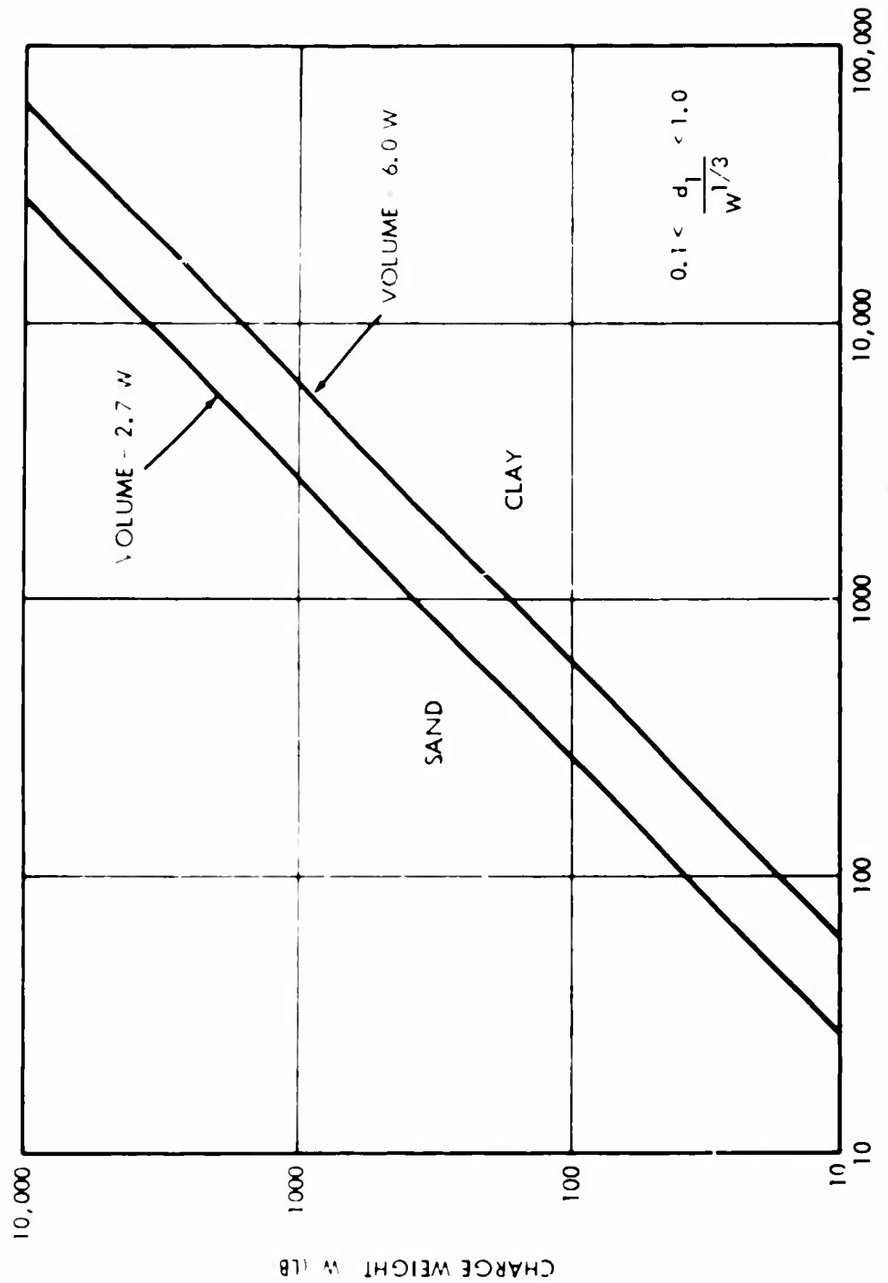

FIG. 19 CRATER VOLUMES

Although the cratering process in soils must be related to the bubble phenomena of a bottom explosion, little is known about the nature of this relationship. The behavior of bubbles on a non-cratering bottom was studied in a vacuum tank, however, and this information is helpful, particularly for very deep explosions. Over a range of depths extending from $d_1/A_1 = 1.7$ to 5.2, the bubble was almost hemispherical in shape, with the diameter of the base averaging 2.30 times the calculated maximum bubble radius in free water. A significant result was the observation that at relatively great depths, the bubble stays on the bottom through all of its oscillations. An example of such behavior is shown in Figure (20). In the absence of other information, it may be assumed that the crater diameter is equal to the bubble diameter for deep explosions.

When the oscillations are completed, the remaining gas doubtless rises to the surface, possibly as a cloud of small bubbles. However, it seems evident that a large fraction of the explosion products would be deposited on or within the bottom in these circumstances. It is not clear how the vacuum tank data should be used for predicting effects on the seabed, and further work is needed to evaluate the model tests, but it seems possible that a pulsating bubble may stick to the bottom when the depth is greater than ten maximum bubble radii. (The free-water value of A_1 is used for convenience in scaling.) This is based on limited evidence from field tests, which show only an upwelling at the surface at this reduced depth.

This is considerably less than the estimated depth for upwelling from free-water shots, and it would be expected that the containment depth would also be reduced for bottom shots. There is no information on which to base an estimate of this depth, however.

A secondary effect of interest is that an explosion on the bottom could possibly release a cloud of natural gases, such as methane, from the bottom sediments. This occurred when Lithanol tests were conducted on the bottom of the Chesapeake Bay. In some cases, a large cloud of small bubbles reached the surface, although no dye tracer was observed and there was no evidence of the arrival of explosion debris.

VII LONG-TERM EFFECTS

Immediately after an explosion, the growth of the surface pool is caused by an upwelling and radial expansion resulting from the migration of the explosion bubble toward the surface. The flow is obviously turbulent, due both to the oscillations of the bubble and the emergence and collapse of plumes of water and spray. During this stage, internal turbulence probably produces a uniform distribution of any products in the water. After the violent motions have subsided, the pool becomes placid, and it is then subject entirely to environmental effects and natural turbulence. In general, it is not clear when this takes place, because the transition is gradual. Natural processes are always present, though secondary in influence at early times, and the pool is transported by currents from the time it first appears at the surface.

When the pool reaches the stage in which it is essentially a part of the environment, except for its contents, it is acted on by relatively large-scale features of oceanic motion that lead to distortion and translation and by small-scale eddies that contribute to the turbulent diffusion process. These effects have been described thoroughly in several publications such as: Wiegel (1964); Smith (1967); Okubo and Pritchard (1969); and Okubo (1970). Reports related specifically to explosion pools include a publication by Koh and Fan (1969).

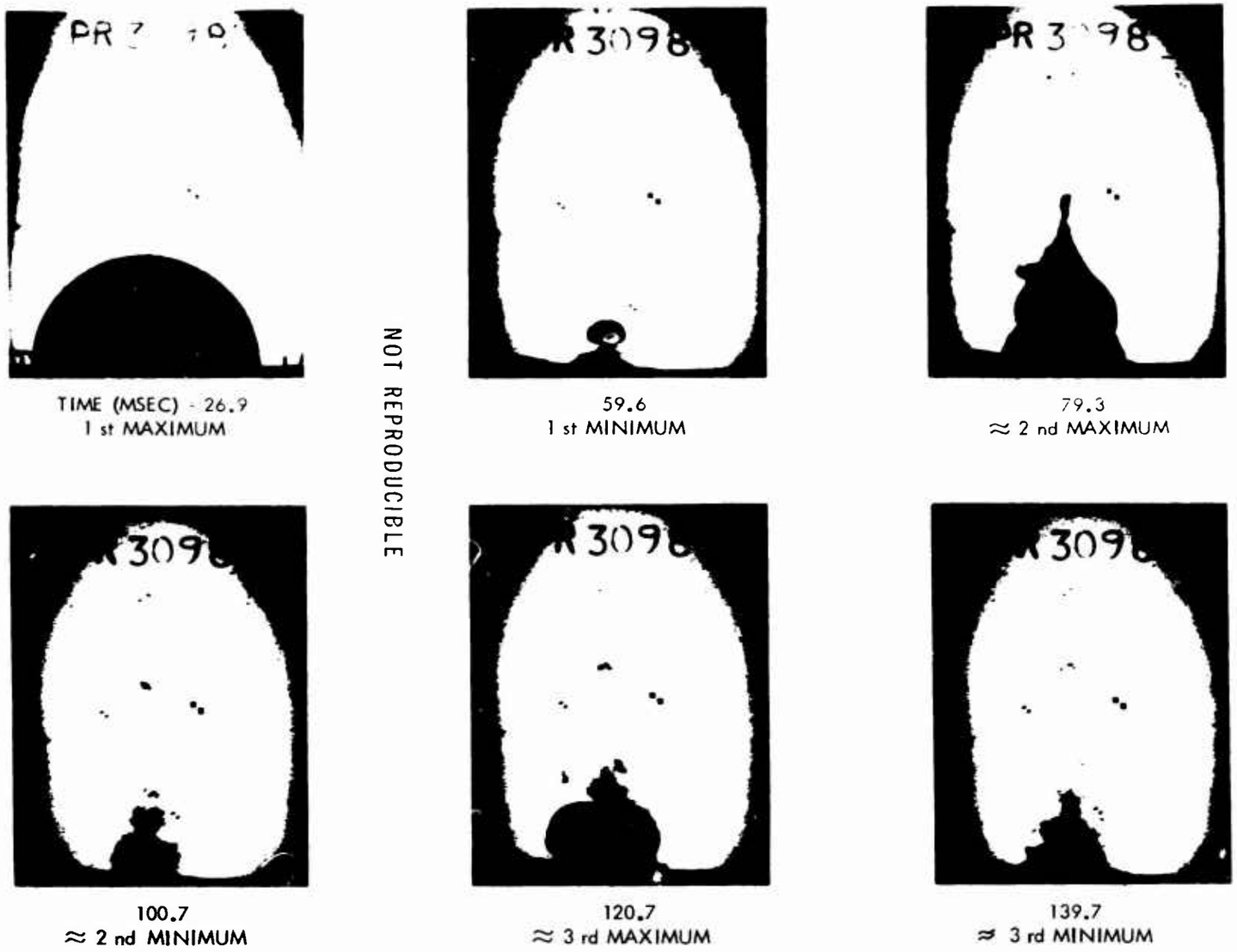

FIG. 20 BUBBLE PULSATING ON THE BOTTOM IN VACUUM TANK EXPERIMENT

If the size of a pool and the quantity of foreign substance it contains at the time of stabilization can be established, it is then possible to calculate the future history of the pool by established methods. These have been summarized in useful formats by Okubo and Pritchard (1969) and by Koh and Fan (1969). If solid particles with an appreciable fall velocity are present, these must be treated separately, as they will settle out of the pool (e.g., Charnell, et al, 1970).

At the present time, Equations 4, 5, and 6 can be used to estimate the size of the surface pools formed by explosions at depths less than 25 bubble radii. In regard to the contents of the pools, the only approach that seems reasonable in view of the current lack of information, is to maximize the amount of entrained material and assume that it is distributed uniformly. For example, if an investigator is concerned about the environmental effects of carbon particles in water, he can assume that all of the carbon from the explosion is deposited in the surface pool, and then calculate its subsequent dispersion. If the effects prove to be of no concern on this basis, then there would be no detrimental effect in a realistic situation.

VIII CONCLUSIONS AND RECOMMENDATIONS

There is only a limited amount of quantitative information on the physical effects of underwater explosions that can be applied directly to the problem of estimating the long-range effects on the environment. In regard to the heating of water by an explosion, however, there is little doubt that turbulent mixing reduces this to a negligible level at an early time and that the temperature differences will be only a fraction of a degree a few minutes after an explosion takes place. Within an hour of almost any explosion, these temperature changes should be indistinguishable from the normal temperature variations observed in natural bodies of water.

However, the mixing of explosion products with the environment is a more complex process because the products may be gaseous, they may possess various degrees of solubility, or they may be particulate in form with a wide range of sizes. To gain more information on this problem, it would not be difficult to conduct a series of underwater explosion tests in the field and sample the surface pools as a function of time and space. The samples could be analyzed chemically and the sizes of particles could be measured. Established tracer techniques could be employed as a backup. However, the acquisition of data concerning the distribution of products in the air and beneath the surface in a natural environment would be a major undertaking. It might be more fruitful to use a large tank, or possibly an experimental pond, for this purpose.

Direct measurements of cratering effects and the deposition of products in the seabed are also feasible, providing the experiments are done in clear water at a depth of 100 feet or less. In this case, underwater photography can be used, and divers could inspect and sample the bottom.

As a supporting effort, it is recommended that the existing photographs of small-scale tests at relatively deep positions in the NOL accelerated tank be fully evaluated. This would provide invaluable information concerning the migration and breakup of explosion bubbles, though the photographs alone cannot answer the existing questions concerning environmental effects.

By combining the data acquired from new field tests, the accelerated-tank data, and existing knowledge of explosion processes, physical chemistry, and oceanic phenomena, it should be possible to develop a computational model for prediction purposes. Such a model was developed at the Naval Ordnance Laboratory for Lithanol explosions. Although it is not valid for explosives that generate bubbles of gas, it could be used to guide the initial effort. A gas bubble model could probably never be precise, but it could be used to establish a reasonable range of the possible physical effects of underwater explosions on the environment.

It is not the purpose of this report to evaluate the degree of harm, or lack of harm, of an explosion to the environment. The research program outlined above would help to put this aspect of the problem on a firmer basis for underwater bursts. However, on the basis of current knowledge alone, it would be possible to do a comparative study of the environmental effects of explosions in the air, on land and water surfaces, and under water and ground. For example, the theories of turbulent diffusion in these media are well established. It is conceivable that underwater explosions at carefully selected sites in deep water would result in the least damage to the physical environment and to living creatures.

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