[redacted]

LA - 545

[redacted]

April 8, 1946 C3 This document contains 24 pages

UNDERWATER EXPLOSION OF A NUCLEAR BOMB

WORK DONE BY:

John von Neumann

Maurice M. Shapiro

REPORT WRITTEN BY:

John von Neumann

Maurice M. Shapiro

[redacted]

[redacted]

ABSTRACT

This report discusses the principal phenomena which are expected to be of importance in the underwater explosion of a nuclear bomb. The pulsations of the underwater bubble created by such an explosion should be qualitatively similar to those of a high explosion. For an efficiency corresponding to 20,000 tons of TNT,* the duration of the shock wave is about 35 milliseconds. The peak pressure in the shock wave is plotted against the range for several efficiencies. The radius of lethal damage due to the impact of the shock wave against capital ships is estimated to be at least 1/2 mile, and it scales as the cube root of the charge weight for explosions of this order of magnitude. In inflicting damage by the shock wave, the depth of the explosion is significant; for a lethal radius of 3000 feet, depths of 1600 to 2000 feet are required. The motion of the bubble and of the water after the radiation of the shock wave are discussed in some detail. The maximum radius of the hollow at the end of its first expansion is approximately 340 feet for a detonation depth of 2000 feet, and the first period of pulsation is about 2 seconds. Damage from the afterflow and the second pressure pulse is expected to be unimportant compared with damage from the shock wave. Because of its large size, the rise of the hollow under gravity will strongly predominate over the repulsion of the surface. This vertical motion of the bubble will be associated with pronounced turbulence and instability.

*The numerical estimates in this Abstract all apply to this efficiency.

[redacted]

APPROVED FOR PUBLIC RELEASE

[redacted]

UNDERWATER EXPLOSION OF A NUCLEAR BOMB

Introduction

The phenomena associated with an underwater explosion have been extensively studied, and their main features are fairly well understood.[1-6] When a charge of ordinary high explosive is fired under water, the explosive is immediately converted to gas under very high pressure (of the order of a million pounds per square inch). About a third of the explosive energy is radiated into the water as a shock wave, or pressure pulse with a very steep front. Meanwhile, the gaseous combustion products form an expanding bubble, which grows until the pressure inside it falls far below the hydrostatic

---

1)"Experiments on the Pressure Wave thrown out by Submarine Explosions," by H. W. Hilliar, British Admiralty Research Experiment 142/19, 1919.

2)"The pressure-Time Curve for Underwater Explosions," by W. G. Penney, Ministry of Home Security, Civil Defense Research Committee, England, R.C. 142, November 1940.

3)"Theory of the Pulsations of the Gas Bubble Produced by an Underwater Explosion." by Conyers Herring, NDRC Report C4-sr20-010, Columbia University, Division of National Defense Research, New London, Connecticut, October, 1941.

4)"Report on Underwater Explosions," by E. H. Kennard, David Taylor Model Basin Report 480, October 1941.

5)"The Pressure Wave Produced by an Underwater Explosion, I" by J. G. Kirkwood and H. A. Bethe, NDRC Report Div. B, Serial No. 252, (1942). Subsequent reports by Kirkwood *et al*: NDRC Serial Numbers 281 and 326 (1942), OSRD No. 2022 (1943), and NDRC Div. 2 Interim Report UE-24 (1944).

6)"Vertical Motion of a Spherical Bubble and the Pressure Surrounding it," by G. I. Taylor, British Report S.W. 19, 1942. Also see British Undex reports.

[redacted]

pressure outside.* Finally the excess pressure outside the gas globe causes it to contract. If the charge is immersed deeply enough, the sequence of expansion and contraction is repeated several times. Thus there occurs a series of pulsations, each accompanied by a pressure pulse and by a mass motion of the surrounding water. The impact of these pressure pulses is mainly responsible for the damage inflicted upon ships by underwater mines.

This report attempts to summarize the principal phenomena which are expected to be of importance in the underwater explosion of a nuclear bomb.

Behavior of the Underwater Bubble from a Nuclear-Bomb Explosion

There is good reason to expect that the character of the pulsations of the underwater bubble from a nuclear bomb will differ only in degree--and not, fundamentally, in kind--from those of a TNT explosion. To be sure, the expanding gas in a nuclear explosion consists almost entirely of water vapor, whereas for an ordinary explosion it is composed of the combustion products. However, to a first approximation, the hydrodynamical theory** of the bubble's behavior is nearly independent of the presence of gas inside the hollow. This is true for a small bubble.[7)]

---

*This overshoot is caused by the inertia of the surrounding water.

**E.g., that of Conyers Herring, Reference 3.

7)Experimental evidence for this has been found by G. I. Taylor and R. M. Davies, who showed that a hollow created by the discharge of a high voltage spark under water produces pulsations like those of the gas globe from an H.E. explosion. (Cf. British Report S.W. 29, Undex 13).

[redacted]

[redacted]

and it should be especially true for a large one.* Hence it may be expected that the usual sequence of oscillations will occur. If the nuclear bomb is set off at a depth of 2000 feet, there should be approximately two pulsations before the bubble disintegrates.

The qualitative differences between the behavior of the bubble from a nuclear bomb and that from an ordinary explosion will arise not from the relative paucity of combustion gases in the gadget explosion, but from its huge scale. Because of its large size, the rise of the bubble under the influence of gravity will strongly predominate over the repulsive effect of the surface. As will be explained below, this rise leads to turbulence and to distortion of the gas globe which may be serious enough greatly to inhibit the second expansion.

Furthermore, the distribution of the orginal explosion energy over various kinetic and potential forms may differ considerably in the case of a nuclear bomb from that in an ordinary high explosion because of the great difference in the original temperatures.

---

* For a large bubble the effect of the gas should be even less important than for a small one. As pointed out by Kennard in TMB Report R-182, "the inward motion of the water during each compression phase is arrested chiefly not by the gas but as a consequence of the conversion of radial kinetic energy of the water into kinetic energy of translational motion." This conversion of energy into migration of the bubble is especially pronounced for a large-scale explosion, as discussed below.

[redacted]

 [redacted]

Partition of Energy

In an ordinary high explosion, according to W. G. Penney,[8] about 30 per cent of the energy is carried away by the shock wave, 40 per cent goes into the pulsating motion of the bubble, and the remaining 30 per cent is lost through the irreversible heating of the water. Direct observations of the bubble's first maximum radius and period confirm this view, for they show that 40 to 50 per cent of the energy goes into the motion of the gas globe.[3,9]

One cannot be sure that the same partition occurs for a nuclear explosion. Since the temperatures involved in the latter are much higher than those in the former, it is reasonable to expect a higher dissipation. In air, we know both theoretically and experimentally that the shock energy for a gadget explosion is about 2/3 of what it would be for an equivalent high explosion.[10] The corresponding theoretical considerations for water are apt to be rather difficult. The experimental decision will have to come with underwater nuclear-bomb tests. At this time it seems reasonable to expect a distribution of energy for the nuclear bomb explosion which is somewhat, but not essentially less favorable than that of a high explosion. We shall therefore assume that 40 per cent of the energy goes into pulsations.

---

8) W. G. Penney, LA Report 215, February, 1945.

9) "Measurements of the Growth and Oscillation of the Bubble Formed by an Underwater Explosion," Undex 35 (1943).

10) LAMS Report 300, September, 1945.

[redacted]

This permits us to scale up the usual high-explosion bubble formulae, as used by C. Herring, G. I. Taylor, and E. H. Kennard, to the nuclear-bomb explosion.

It should be noted that the energy of the bubble pulsation is contained in three main categories among which continuous interconversions take place. These are:

(a) The kinetic energy of the flow of water around the bubble.

(b) The potential energy associated with the existence of an underwater cavity in a region where hydrostatic pressure exists.

(c) The internal energy of the gas in the bubble.

Between two successive pulses part of this energy is lost through acoustic radiation. However, these losses, with the exception of the first one (which is of the order of 30 per cent) are small, and we need not be concerned with them here.

The Shock Wave

At the moment of detonation a pressure pulse with an exceedingly steep front is radiated into the water. This so-called shock wave has at first a velocity considerably in excess of sonic, but at distances of about 30 or more charge diameters, it acquires a nearly acoustic velocity.

The time of rise of the initial pressure pulse from an explosion of 1 lb. TNT under water is of the order of 1 or 2 microseconds. The decay of the shock wave is approximately exponential, so that it can be described by

$$p = p_m e^{-t/\tau}$$

where p is the pressure at the time t, and p_m is the peak pressure.

[redacted]

The duration is defined as the time τ required for the pressure to fall to 1/e of its peak value. τ varies somewhat with the distance from the charge, but its variation is rather slow. According to the asymptotic theory of Kirkwood and Bethe,[5] for large distances r it increases as $(\ln r)^{\frac{1}{2}}$. Over the range which interests us, an $r^{.1}$ power law is reasonably adequate. This means that in this region (pressures from a fraction of a ton per square inch to about ten tons per square inch) in which the distance changes by a factor of about 10, the duration changes only by about 25 per cent. For one pound TNT, τ is approximately 0.105 millisecond. Since these times scale as the cube root of the charge weight, we should expect for a 20,000-ton bomb explosion under water a duration of approximately 36 milliseconds.

Peak Pressures

The estimates given below of peak pressure as a function of distance from the explosion are based upon an extrapolation of empirical data for TNT obtained at the Underwater Explosives Research Laboratory, Woods Hole, Mass.[11] These data yield the following power law, which is plotted in Figure 1:

$$P_m = 21,100 \left(\frac{W^{1/3}}{R}\right)^{1.17}$$

[redacted]

where P_m is the peak pressure in pounds per sq. in., W is the weight of explosive in pounds, and R is the distance in feet.

For our purposes this may be expressed as $P_m = A R^{-1.17}$ where A is a function of the equivalent weight of TNT.

---

11) NDRC Division 2 Interim Report UE-23 (CONFIDENTIAL), July 15, 1944.

For 10,000 tons, $A = 1.485 \times 10^7$

20,000 tons, $A = 1.946 \times 10^7$

30,000 tons, $A = 2.279 \times 10^7$

It will be seen in the next section that for charges smaller than 100 tons, the peak pressure alone does not determine the damage. For charges greater than 100 tons we expect it to be the only significant quantity.

Lethal Range of a Nuclear Bomb

The criteria which should be used in determining the lethal range of a ship from an underwater explosion depend upon a number of variables, of which the most relevant will be considered here.

We consider first the effects of the shock wave. An important factor is the relative duration of the initial pressure pulse and the natural vibration period (or rather, half-period) of the panels in the hull of the ship, especially the bottom. If the pressure pulse lasts longer than the natural period, the blast acts essentially as a static pressure, and therefore the peak pressure alone is relevant; otherwise the duration of the pulse, and indeed the detailed structure of the pressure-time curve must also be considered. A more detailed analysis of the mechanical phenomena associated with impact damage shows that the integrals $\int p^2\, dt = E =$ energy, or $\int p\, dt = I =$ momentum, are the main determining quantities, according to whether cavitation does or does not occur. If cavitation does occur, most of the kinetic energy in the pressure pulse is trapped in a layer of water close to the hull.

[redacted]

  [redacted]

In this event, and assuming that the duration of the pressure pulse is sufficiently short, the energy in the shock wave is a good criterion of the damage to be expected. Moreover, in scaling up the damage in this case, an approximately correct scaling factor is the square root of the original explosion energy (or, what amounts to the same thing, the square root of the charge weight), since the dishing of a target diaphragm is proportional to this factor. This is what we should expect theoretically, but British data on damage to capital ships suggest that the factor $W^{.42}$ fits the facts better.[12)]

When cavitation does not occur, the momentum may be used as a criterion of damage, again assuming that the pressure pulse does not last too long. This leads to a $W^{2/3}$ law for the following reason: Similarity considerations show that distances and durations scale at equal pressure levels as $W^{1/3}$. Thus at $W^{1/3}$-fold distances r, the momentum scales as $W^{1/3}$. Now the momentum appears to be proportional to r^{-1}.[13)] Hence equal momenta occur at distances which scale with $W^{2/3}$

For pressure pulses of long duration the peak pressure alone matters, as explained above. This means that the scaling is governed by a $W^{1/3}$ law.

It may be asked, What is the lethal range of a gadget from a capital ship? The duration of such an underwater explosion should be about 35 milliseconds. The periods of the main components of capital ships (e.g., bottom panels, stiffened main bulkheads, etc.) which are exposed directly or indirectly to this blast are of the order of 10 to 15 milliseconds. Hence the duration of 35 milliseconds is 5 to 7 times as long as the half periods which matter. For a 100-ton charge the duration is 6 milliseconds; hence the

12) Table I, U.S. Naval Attache, London, Letter #L-195 Dated 22 December 1942.

13) R.W. Goranson, Underwater Explosion Report No. 1944-1 (NavShips-374), February, 1944, Figure 2.

[redacted]

[redacted]

peak pressure criterion is probably valid all the way from 100 tons to the gadget size of about 20,000 tons. In other words, in this range distances may be scaled according to the $W^{1/3}$ law.

The question remains, How shall we estimate the lethal range of 100 tons, since most actual experience comes from charges weighing between a few hundred pounds and 1 ton, and none from more than about 3 tons. This question is best considered together with another, closely related one, i.e., What constitues lethal damage?

For the conventional charge size of mines and torpedoes, from a few hundred pounds to a ton, the nature of lethal damage is rather complicated. In particular, for a well-contructed naval vessel with adequate compartmentation and efficient damage control, mere piercing of the ship's outer walls, or even of all its skins, will only exceptionally constitute lethal damage. It will, as a rule, lead to the flooding of only one or two compartments. Indeed, modern capital ships will normally be sunk only by a considerable number of mine or torpedo explosions. Thus, a local leak which produces flooding of the adjacent compartments is not lethal damage for charges of this size.

We note, however, that the distances at which charges between a few hundred pounds and a few tons can cause this type of damage, "serious flooding," are reasonably well known. Curves for W = 500 to 5000 pounds have been given.[12) They apply to incidents in which the depth of the explosion was sufficient to direct the blast at the ship's bottom, and not only at its more deeply protected sides.

[redacted]

[redacted]

These observations are adequately represented by the formula

$$R = 92\ W^{.42}$$

where R is expressed in feet and W in tons ($\frac{1}{2} \leq W \leq 5/2$).

As pointed out above, this "serious flooding" inflicted over distances of the order of a hundred feet is not lethal. A larger charge will inflict it over considerably larger distances. If these are of the order of a capital ship's length or more, i.e. of the order of 800 ft. or more, then the significance of this damage changes; the entire ship's length may be opened up, and all or most compartments flooded simultaneously. This is presumably lethal.

Let us therefore estimate what the distance of serious flooding is for a nuclear bomb of 20,000 tons. We know that the scaling law up to 2.5 tons is $W^{.42}$, and above 100 tons it is $W^{.33}$. We have no information as to what law is valid between 2.5 and 100 tons, but it is very plausible that it will be between these two powers. Now the interval from 2.5 to 100 tons corresponds to a factor 40. Therefore, the $W^{.42}$ law scales up by 4.7, whereas the $W^{.33}$ law scales up by 3.4. Taking the mid-value of these two factors, 4, we make an error of at most 17 per cent. Considering all other uncertainties, such an error seems not excessive. Consequently, the distance of serious flooding may be taken, for $W = 2.5$ tons, as $R = 92\ (2.5)^{.42} = 135$ ft. For $W = 100$ tons, we multiply this by 4, getting $R = 540$ feet. For a bomb of $W = 20{,}000$ tons, we multiply this by $\left(\frac{20{,}000}{100}\right)^{1/3} = (200)^{1/3} = 5.85$ getting $R = 3160$ feet, somewhat over 1/2 mile.

[redacted]

UNCLASSIFIED

 [redacted]

Thus the radius of serious leakage is large enough to qualify this type of damage as lethal according to our discussion above.

To summarize, the lethal damage radius due to the shock wave of a 20,00-ton nuclear bomb against capital ships is at least 1/2 mile, and it scales in this region as $W^{1/3}$. We made it clear that this prediction depends on a number of hypotheses. Short of a full-scale nuclear-bomb test against ships, a partial scale test at the lower end of the $W^{1/3}$ range, i.e. a test with a high explosive charge of 100 tons or more would seem most desirable.

Depth of the explosion.

In inflicting damage by the shock wave, another factor is of importance; the depth of the explosion. Indeed, unless the explosion takes place essentially under the ship, the shock will have hit the sea surface before striking the target. Now the sea surface reflects the shock, but since it is a free surface (and not a rigid wall) it reflects it negatively as a rarefaction. Thus the shock arrives at the target immediately followed by this rarefaction. Throughout the area which it occupies, the rarefaction removes the high pressures which follow the shock front. Hence it is important that it should not get nearer to the shock than the distance within which are found the over-pressures needed to inflict damage. We have seen that blast pressures lasting about one-half of the significant elastic periods are the essential contributors, i.e. that the first 5 to 7.5 milliseconds matter. Since the blast velocity is essentially acoustic, and since sound velocity in water is 5000 feet per second, this means that 25 to 37.5 feet of the blast zone must be kept intact. The depth at which this is required is the depth of the ship's bottom, i.e. about 30 feet.

[redacted]

APPROVED FOR PUBLIC RELEASE

 [redacted]

Thus the geometry of the phenomenon shows that the angle between the blast and its reflection must be at least 60°; see Figure 2. Hence $\beta = 60^\circ$ and $\alpha = \frac{1}{2}(180^\circ - \beta) = 60^\circ$. Now the depth of the explosion must be at least $\sin \alpha$ times the distance at which the damage is to be effective, i.e. at least 1/2 that distance.

Thus for the lethal radius of 3160 feet mentioned above, an explosion depth of at least 1600 feet is required. If weaker ships are targets at larger distances, still greater depth are desirable.

It seems, therefore, that depths of 1600 to 2000 ft. will be the significant ones.

MOTION OF THE BUBBLE AND OF THE WATER AFTER THE SHOCK

Afterflow

Experimental pressure-time curves show that when the pressure in the shock wave has fallen to a few per cent of its maximum value, its subsequent decay is not even approximately exponential, but considerably slower than this. This lower pressure, which lasts many times as long as the shock wave, is associated with the so-called "afterflow," or radial motion of the water--now behaving as an incompressible fluid--around the gas globe. A theoretical expression for this pressure has been derived by G. I. Taylor.[6] Although its magnitude is only a few per cent of the peak pressure in the initial pulse, its duration is so long that its impulse cannot, *a priori*, be neglected in considerations of damage. It will be shown below, however, that the afterflow from a nuclear-bomb explosion is unlikely to contribute significantly to the damage.

UNCLASSIFIED [redacted]

First Expansion of the Bubble

The radiation of the shock wave is followed by an expansion of the gas globe, which imparts a high radial velocity to the surrounding water. Because of the inertia of the water, this expansion continues until the pressure inside the globe is far below the hydrostatic pressure at the level of detonation. At the end of its first expansion the radius of the bubble from an underwater explosion of TNT is given by[14]

$$R_m = 160 \left(\frac{W}{P} \right)^{1/3}$$

where R_m is the maximum radius in feet

W is the charge weight in tons

p is the total pressure (atmospheric plus hydrostatic) in equivalent feet of water.

For an explosion of 20,000 tons, the depth at which the globe would just break surface at its maximum size is 530 feet. The maximum radii for other initial depths of a gadget of this size are:

Depth (ft.)	Radius (ft.)
1000	430
1500	380
2000	340

UNCLASSIFIED [redacted]

14) This was first shown by A. Ramsauer, Annalen der Physik, 4th Ser., 72, 265 (1923). It has been verified in recent British experiments described in S.S. Report No. 1215, Undex 35 (1943).

[redacted]

These figures should be increased by 14 per cent for 30,000 tons, and decreased 21 per cent for 10,000 tons.

Period of Pulsation

When the expansion of the bubble has been arrested, the surrounding hydrostatic pressure causes a contraction to set in. The latter continues until the radius is reduced to approximately one-half of its maximum value. The period T of this first pulsation cycle (from the moment of detonation until that of peak recompression) is given theoretically by[3]

$$T = 1.135\, \rho^{1/2}\, p^{-5/6}\, E^{1/3}$$

where ρ is the density of the water

p is the total hydrostatic pressure at the level of detonation

E is the energy which goes into the bubble pulsations, estimated at 0.4 of the total energy released by the explosion.

For a 20,000-ton nuclear bomb exploded at a depth of 2,000 feet, the predicted period is 1.9 seconds. If we scale up the experimental results of Taylor and Davies,* we get a somewhat larger value, 2 seconds. In subsequent cycles the period increases, approaching a duration about twice that of the initial period.[3]

UNCLASSIFIED

*See Figure 10, Reference 7.

[redacted]

Second Pressure Pulse

During its recompression the gas globe sends out into the water a second pressure pulse which differs markedly from the first one. The maximum pressure in this second pulse is less than 10 per cent of that in the shock wave. Its duration, on the other hand, is of the order of a hundred times that of the shock wave, so that the impulse associated with it is ten or more times as large as the impulse delivered by the shock wave. It should be noted that the rise of pressure is very gradual compared with the sharp rise at the shock front, and the pressure decay is also much slower than that in the shock wave. Altogether, the second pulse is more like an acoustic wave than a shock wave.

Nevertheless, because of the large momentum associated with it, the second pressure pulse can, under certain conditions, inflict considerable damage upon a target. This damage may be enchanced by the rise of the gas globe which brings the source closer to the target than it was at the time of detonation.[6] (The nature of this vertical motion will be discussed below.)

Damage from the Afterflow and the Second Pressure Pulse

It has been pointed out that the pressures in the afterflow and in the second pulse are of the order of only a few per cent as large as that in the shock wave. They are of interest mainly because of their long duration, which results in a large impulse.

[redacted]

In fact, these pressures may be considered to be static with respect to the half period of a typical target structure. Where the total impulse is an important criterion of damage, they may consequently contribute appreciably to the damage.

In the case of a nuclear-bomb explosion, however, the shock wave itself, lasting for a time of the order of 35 milliseconds, is also, in effect, a static pressure. As we have seen, this is why the peak pressure is the significant criterion of damage for explosions of this magnitude. Moreover, the peak pressure in the shock wave is so much greater than the pressures associated with the afterflow and the secondary pulse that is is likely to inflict far greater damage than the latter. In fact, within the lethal radius calculated elsewhere in this report, the damage caused by the shock wave alone should be decisive.

According to the simplest theory we might expect that the rise of the gas globe under gravity would enhance the damaging power of the second pressure pulse, which originates closer to the target than does the shock wave. However, in order for this effect to be appreciable, the explosion would have to occur almost directly under the ship. If it occurs elsewhere, the bubble's rise would result in a cancellation of the second-pulse pressures at the target by the reflected rarefaction wave, as explained above in the discussion of the depth of explosion. Even if the nuclear bomb explodes directly under the ship, the asymmetry and turbulence associated with the contraction of a very large under-water bubble will further reduce the damaging effect of the secondary pulses.

Vertical Motion of the Bubble

As the gas globe pulsates it also undergoes vertical displacement under the influence of gravity and of neighboring surfaces. The effect of gravity is,

[redacted]

of course, to give the bubble an upward acceleration. When the globe is near a free surface, it tends to be repelled away from the surface; near a rigid surface it is attracted toward the surface. The physical causes of these surface-proximity effects have been discussed by Herring[3)] and by Kennard.[15)]

For very large charges the rise under gravity predominates over the surface effects since the ratio of the two velocities is given by*

$$5 \quad \frac{\rho g h}{p} \quad \frac{h}{R_m}$$

where p is the total hydrostatic pressure at the detonation level

h is the depth of this level from the free surface

R_m is the maximum radius of the gas globe.

For a 20,000-ton bomb set off at a depth of 2000 feet, $\frac{\rho g h}{p} \doteq 1$, and $R_m = 340$ ft. So the upward velocity due to gravity is of the order of 30 times that caused by neighboring surfaces.

Let us consider the migration of the bubble during its first period. Most of the upward momentum is acquired while the bubble is large, i.e. when its radius is near the maximum, since the buoyancy is then greatest. However, nearly all of the rise occurs during the contraction phase. The vertical momentum is then concentrated in a relatively small mass of water surrounding the contracted globe,

---

* Reference 3), Appendix 4, Eq. (36).

15) TMB Progress Report, R-182

[redacted]

[redacted]

which therefore acquires a high velocity. According to Herring's theory this velocity is given by

$$\frac{2g}{R^3}\int_0^t R^3\,dt$$

where R is the radius of the globe at the time t. From this one can see that there is a rapid acceleration when the bubble is small.

One of the main reasons for interest in the vertical motion of the gas globe is that for a charge exploded directly under a ship the bubble will have approached the target during its first period, and consequently the pressure pulse radiated at the end of that time will have a shorter distance to travel, be more intense upon its arrival at the target, and have a correspondingly greater chance of contributing to the damage. An approximate theoretical formula for the total rise during the first period, based upon the assumption that the gas globe remains spherical, is[15]

$$\Delta y = 5900\,\frac{\sqrt{W}}{p}$$

where Δy is the rise in feet during the first period,

W is the weight of charge in tons,

p is the total pressure at the level of detonation in equivalent feet of water.

Thus, for a 20,000-ton bomb fired at a depth of 2000 ft., the predicted rise during the first period is 410 feet; at a depth of 1000 feet the rise would be 800 feet.

[redacted]

[redacted]

Actually the foregoing results are overestimates, as they are based on the assumption of spherical symmetry. A small spherical volume would imply a small radius, and this in turn would lead to a very rapid rise. The experimental fact is, however, that the gas globe, instead of remaining spherical, acquires a mushroom shape as it contracts and rises.[7] Thus, although its minimum volume is small, the bubble has a horizontal radius which is considerably larger than it would be if the bubble were spherical, and consequently its rise is slower than predicted by the idealized theory.

Another reason why the rise is slower than predicted by the simplest theory is that the globe does not contract as much as would be expected according to that theory. As mentioned previously, the translational kinetic energy of the water flowing from the top to the bottom of the globe as it rises is obtained at the expense of the kinetic energy of radial motion. Hence the minimum volume at the end of the first period is not as small as it would be if the globe were stationary.

Estimates of the vertical velocity of the bubble from a 20,000-ton bomb fired at a depth of 2000 feet can be obtained by scaling up the results of Taylor and Davies.[7] Their experiments show that this velocity fluctuates, but that it can be described approximately as follows. The bubble is practically stationary during the expanding phase of the first period. During the second half of the first period and the expanding phase of the second period, the average velocity is about 200 feet per second. This rapid rise is followed by another relatively stationary interval toward the end of the second period. The time during which the velocity has the mean value of 200 ft. per sec. is about 2 seconds; hence the rise during the first two periods is about 400 feet.

[redacted]

 [redacted]

Asymmetries

The only available theory of the behaviour of the gas globe assumes that spherical symmetry is maintained. In practice, this is by no means the case. Distortions in the shape of the gas bubble arise principally from the action of gravity and the effects of neighboring surfaces.[7, 16] As we have seen, the former effect strongly predominates for large-scale explosions.

Departures from spherical shape are especially likely to occur during the contraction of the globe. As the bubble rises, there is a flow of water around it from top to bottom, which is faster the larger the globe. This flow may give rise to a considerable turbulence, which results in a dissipation of energy. There is experimental evidence, especially from motion pictures taken under reduced atmospheric pressure, that the globe tends to become mushroom-shaped.[7]

All these effects should be greatly accentuated for the gas globe produced by the explosion of a nuclear bomb. In fact, the turbulence and instabilities arising during contraction may actually cause the bubble to break up. This is more likely to occur during the second contraction than during the first one.

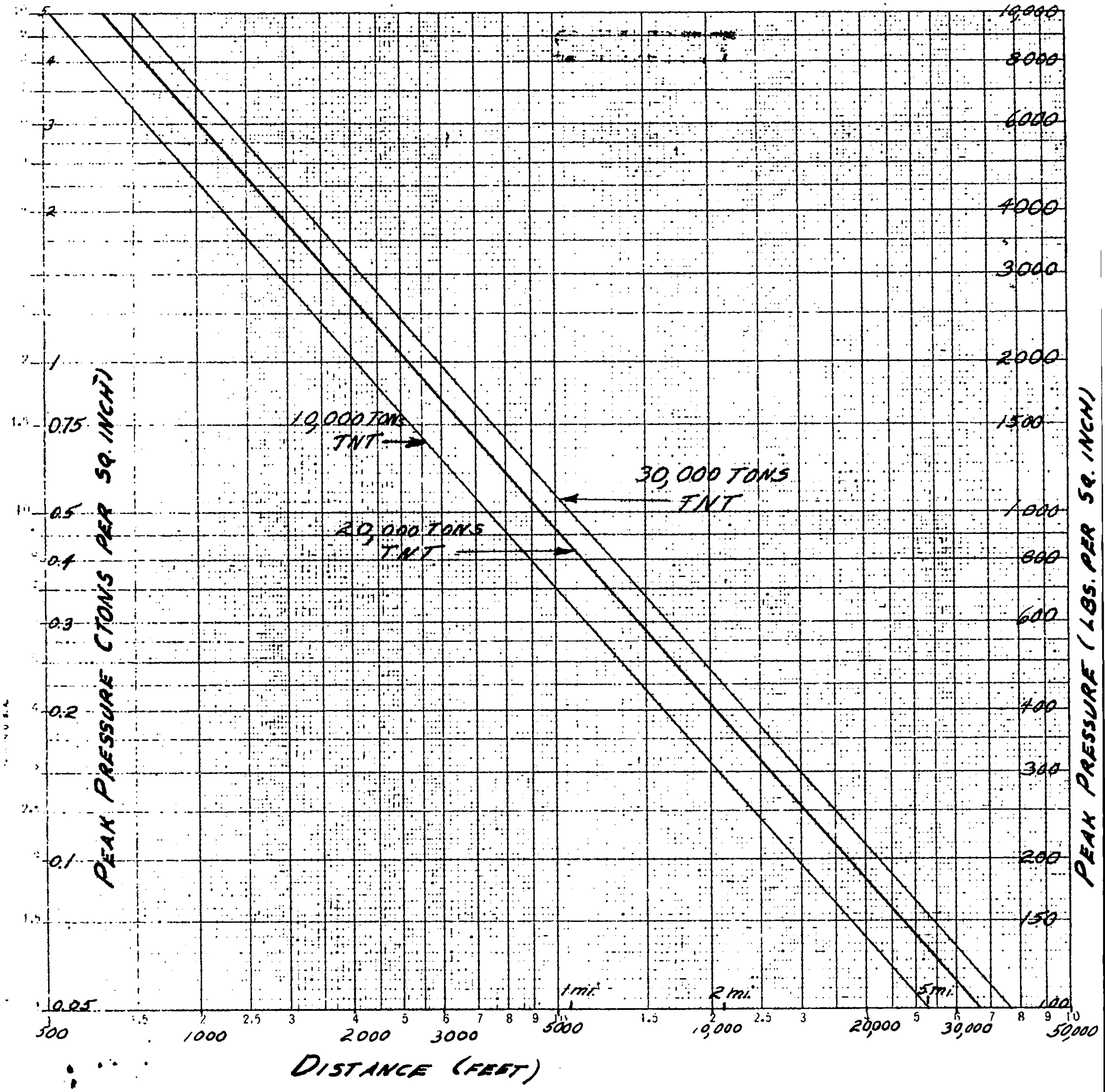
---

16) TMB Reports 512 and 520 (1943) by D. C. Campbell and C. W. Wyckoff, David Taylor Model Basin, USN.

[redacted]

UNDERWATER EXPLOSIONS

ESTIMATED PEAK PRESSURE AS A FUNCTION OF DISTANCE FROM EXPLOSION OF GADGET



[redacted]

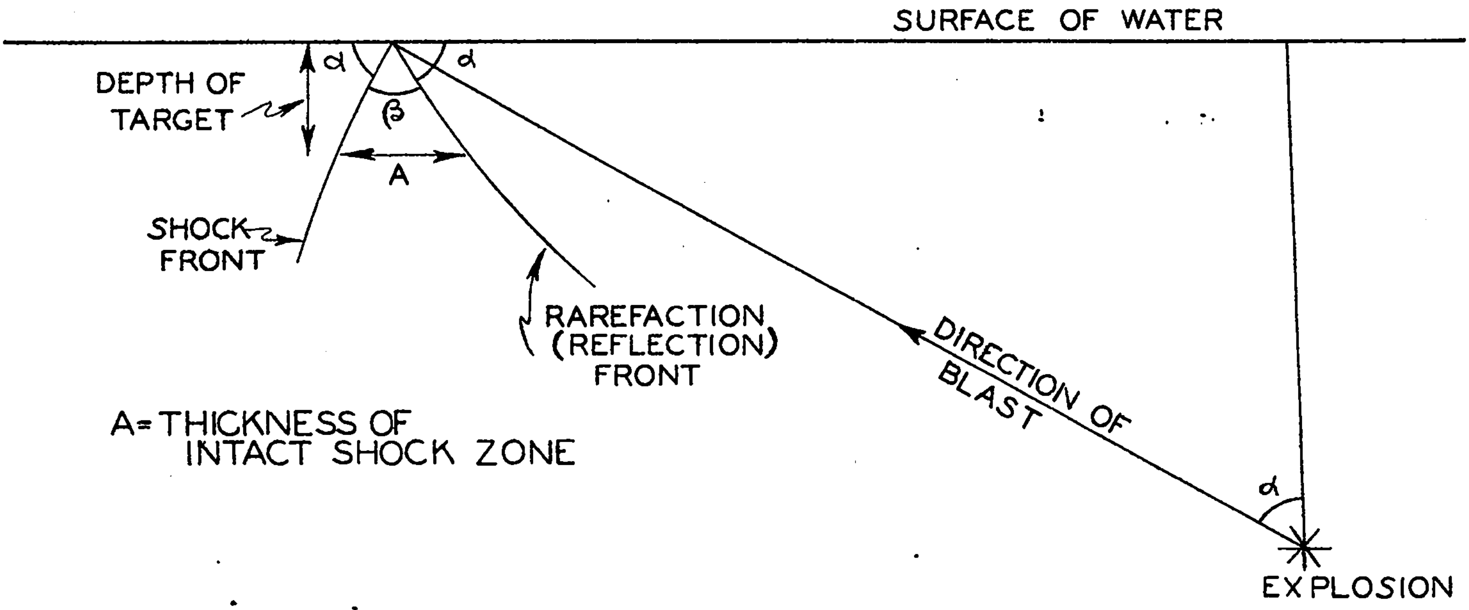


FIGURE 2. GEOMETRY OF SHOCK WAVE REFLECTION ILLUSTRATING REQUIRED DEPTH OF EXPLOSION

UNCLASSIFIED

UNCLASSIFIED

DOCUMENT ROOM

REC. FROM La

DATE 4/22/46

REC. NO. REC.

UNCLASSIFIED

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE