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TORPEDO PROTECTION SYSTEMS
PRELIMINARY DATA ON THE UNDERWATER SHOCK WAVE

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INTRODUCTION

Experimental studies of elementary torpedo protection systems for ships have advanced to a point where a preliminary statement of results is in order.

A summary treatment of the dynamical phenomena in the field of an underwater explosion was embodied in TMB Report 480, recently issued. A simple theory of the dynamical response of a steel structure to very brief transients is included in TMB Report 484, and the same topic also forms the subject of TMB Report 481, both now in preparation.

Preliminary data on the response of a steel cylinder filled with water to explosion of a detonator cap in the axis of the cylinder have now been obtained. Application of the simple theory to analysis of these data yields some results of interest. In view of the current importance of the subject the analysis and results are presented herewith in a form which makes reference to other sources of information unnecessary.

The two phases of explosive action on structures in the field are the shock and the surge, designated as A and B respectively. For present purposes the B phase is ignored. Effects subsequent to the initial rise of pressure are in any case not amenable to study by the present method.

This is not to say that the A phase does all the damage in full-scale attack; but for present purposes, it is assumed that the B phase could not cause actual damage if it were not preceded by A; the latter is therefore the controlling element in the action.

THE TEST ASSEMBLY

This consists of two parts. The first is a steel cylinder 36 inches in diameter, having a wall thickness of 3/4 inch. Its axial length, not a critical dimension, is 60 inches. The second part is a plane diaphragm closing the bottom of the cylinder. In the present tests this diaphragm had a thickness of 3/8 inch. The cylinder is butt-welded along a single longitudinal seam; the joint is not an important feature in the present test. The diaphragm is bolted to a flange of light proportions, so that edge constraint of the diaphragm possesses negligible rigidity, both against rotation in the radial section and against radial tension. These details are shown in Figure 1.

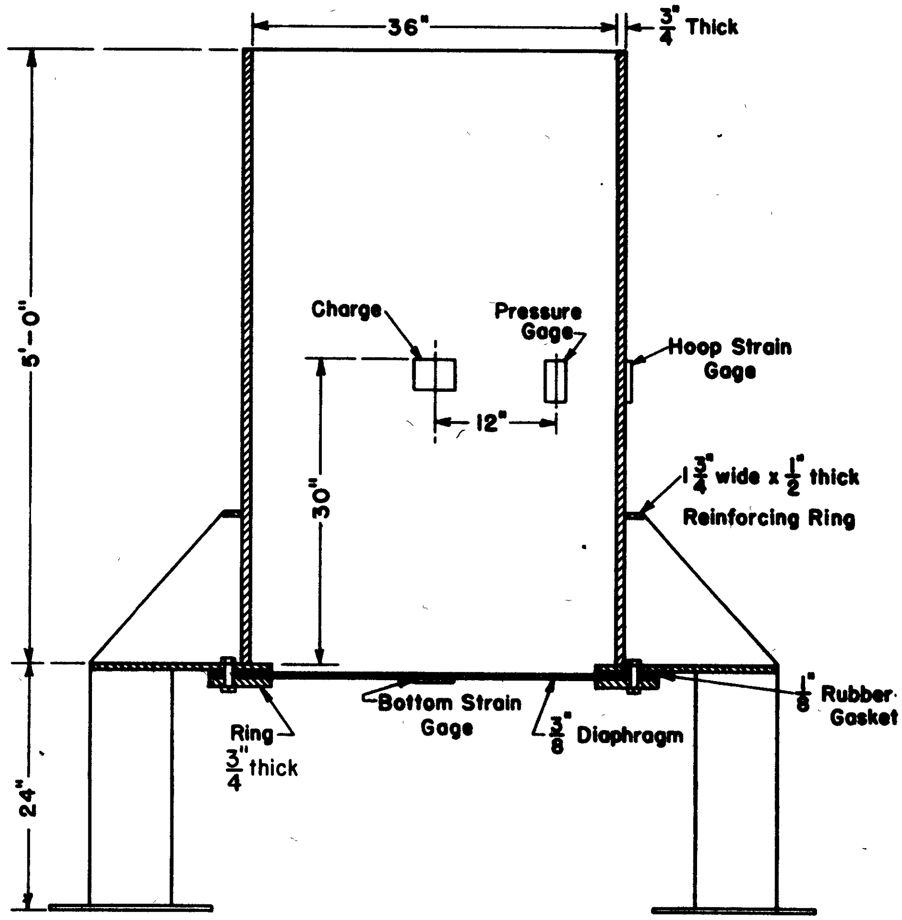

Figure 1 - Vertical Section through the Test Assembly

The cylinder stands on three legs, to make the bottom accessible, and is filled with water.

The weight of the whole assembly is suspended from three points on the cylinder wall; these points are supported by legs which stand clear of the bottom as seen in the photograph, Figure 2.

LOAD

The charge is placed in the axis, at a distance from the diaphragm of 30 inches in most cases, less in a few cases. The shock front is pictured as a spherical shell moving radially outward from the charge. When after 18 inches of travel this shell reaches the wall of the cylinder, the steel undergoes an abrupt tensile action in what may be called the equatorial region, or section through the charge normal to the axis. The initial phase of this action is regarded as simple hoop tension. As the shock front advances farther the section in which the initial load occurs moves axially in both directions, and the stress at the equator is subject to a complex variation further complicated by phenomena of reflection. No attempt is made to follow these variations.

In a similar way, when the shock front has moved along the axis to the point of intersection with the diaphragm, a normal pressure is exerted, and as time goes on, the area on which this pressure acts spreads out from the center. Later phases are confused by reflections from the wall, but these are subsequent to the initial shock.

In both the wall and the diaphragm the load is applied progressively to areas farther and farther removed from that which first receives it; however, this progression is so fast that the phase differences are neglected and the load is considered to be applied over a large area simultaneously.

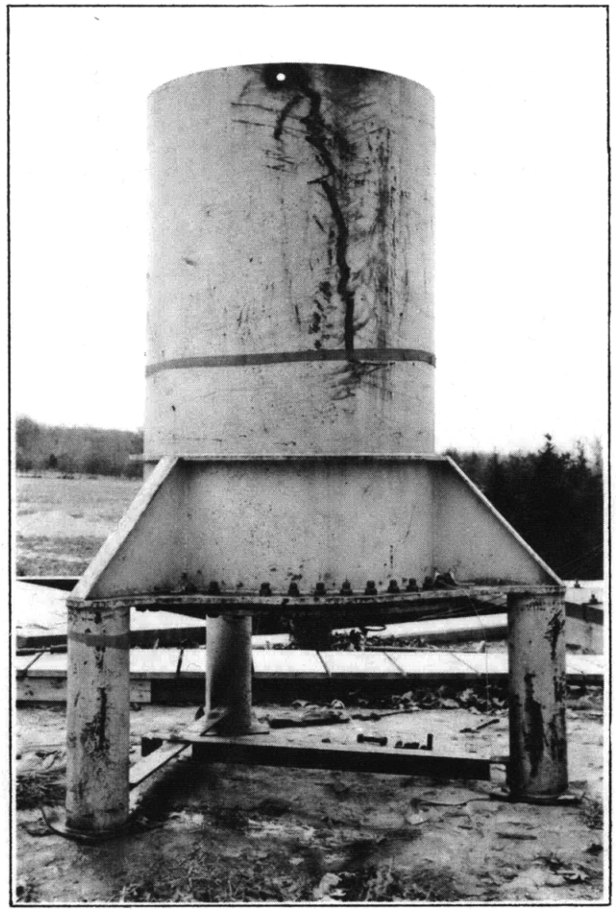

Figure 2 - General View of the Test Tank

The load is assumed to be impulsive, so that its duration is a moderately small fraction of a cycle of natural vibration of the structure on which it acts. The error in this assumption is subject to rough numerical check, as will presently be seen.

The charge consists of a single detonator cap (in one case combined with 15 grams of TNT). The data obtained do not all refer to the same specific explosion, so that comparison of different effects is valid only if the caps are uniform. Variations in the explosive effect of the caps do exist, but for present purposes these are ignored.

To determine the actual characteristics of the load, a completely calibrated and verified high-speed oscillographic pressure gage would be necessary. Although this is not yet available, rough preliminary data have been obtained from a gage consisting simply of a resistor embedded in rubber, which has been subjected to static calibration. An oscillogram obtained from such a gage placed 12 inches from the cap is shown in Figure 3. It shows the initial pulse rising to a peak of 760 pounds per square inch and falling to

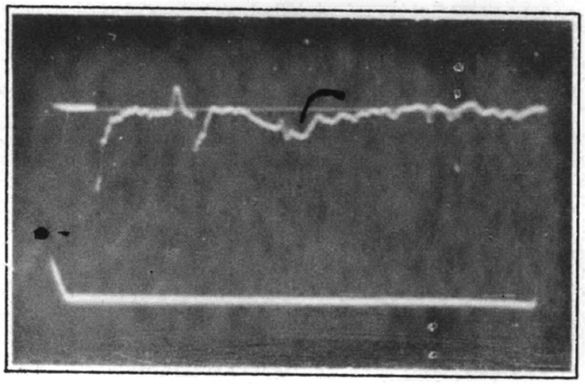

Figure 3a - Oscillogram

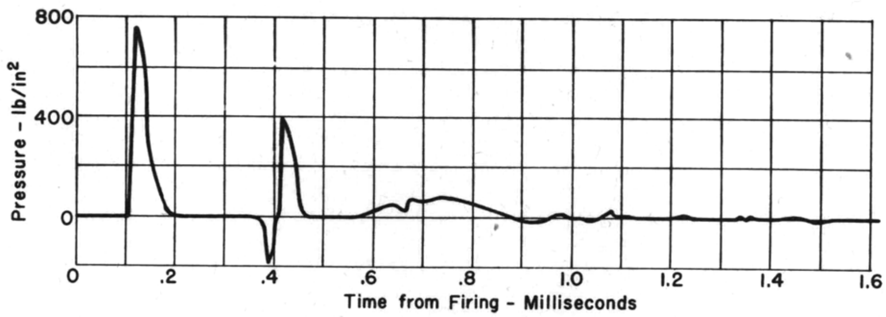

Figure 3b - Pressure-Time Curve Traced from Figure 3a

Pressure peak 750 pounds per square inch. Duration of initial impulse 70 microseconds.

Figure 3 - Pressure in the Field of a Detonator

This pressure was indicated by a rubber-covered resistor gage 12 inches from the center of the explosion.

zero after 70 microseconds. Confirmation of these results by other gages of the same type is available, but not by gages of other types.

For nominal treatment, it may be assumed that the height of the first pressure peak is proportional to the reciprocal distance from the center of the charge, and to the cube root of the weight of charge. Duration of the pulse remains unchanged with distance.

Peak pressure from the single detonator on the equatorial section of the cylinder is thus found to be 12/18 x 760 = 507 pounds per square inch, and on the bottom, 30 inches from the charge, 304 pounds per square inch.

ELASTIC CHARACTERISTICS OF THE STRUCTURE

Both the cylinder and the diaphragm can respond to dynamic load in a great variety of ways, and the records obtained show that they actually do so. The confusion is so great that it is difficult to find any clue to proper interpretation of the record except in the initial rise of the observed quantity.

The whole analysis now to be offered is concerned with the initial development of strain at two stations, one in the equatorial section of the cylinder, and one at the center of the diaphragm.

Strain at these points cannot follow the load, because of the intervening effect of inertia. The transient load is very brief. It imparts suddenly a high velocity to the metal, but the resulting motion after cessation of load is nevertheless strongly affected by the load. In the same way contact between a bat and ball is brief; after it ceases, the motion of the ball continues under control of weight and air resistance. But the impulse imparted by the bat determines the subsequent motion of the ball. And so, from the nature of the initial motion in the cylinder and diaphragm, the nature of the initial impulse of the explosion can be inferred, provided the elastic characteristics of the system are known.

Ignoring complications, the simplest mode of motion in each case is assumed to be the only mode. The cylinder can pulsate as a circular hoop of which only the radius changes, the form remaining truly circular and all sections pulsating together. The natural frequency of such a pulsation is

$$\text{Hoop frequency } f = \frac{1}{2\pi r}\sqrt{\frac{Eg}{\rho}}$$

in which r is the radius of the cylinder

ρ is the weight density of the metal

E is Young's Modulus

g is the acceleration of gravity

In the present case, $r = 18$ inches and by the formula, $f = 1787$ cycles per second. The formula takes no account of the inertia effect of the water, which will reduce the natural frequency by an amount which may be considerable.

Calculation of the frequency of the diaphragm is still more uncertain, but an estimate is possible. For full fixation a calculated value is 113 CPS, for no fixation 43 CPS; and the inertia of the water, as before, will act to reduce the frequency. The formula used in these two cases is

$$\text{Frequency} = \frac{\text{constant}}{2\pi}\,\frac{t}{r^2}\sqrt{\frac{gE}{\rho}}$$

in which r is the radius of the diaphragm

t is the thickness of the diaphragm

g, E, and ρ are as for the cylinder, and the

constant = 1.164 for the case of free support, or

2.945 for the case of constraint.

Frequencies of the order of these calculated values are distinguishable in the oscillograms, although confused by the occurrence of others. The extent to which these fundamental frequencies predominate in the initial phases of the action serve to measure the extent to which the simplified analysis which follows may be accepted as a first approximation.

CALIBRATION OF PRESSURE GAGE

From the data obtained it is possible to infer effective values of impulse, whence a check is obtained on the indicated peak values of pressure.

For this purpose the responding structural system is considered to act like a ballistic pendulum. From its maximum deflection its initial velocity is calculated. This, multiplied by the mass of the moving parts, gives the momentum imparted by the impact of the shock wave.

(a) In Figure 4 the hoop strain is seen to reach a maximum value of about 2.25×10^{-4} inch per inch in 160 microseconds. The strain rate is thus 1.41 inch per inch per second. The corresponding radial velocity outward is $1.41 \times 18 = 25.3$ inches per second.

The steel in an axial length of cylinder of 1 inch weighs 24 pounds.

The momentum imparted to the steel is thus $25.3 \times 24 = 607$ pound mass-inch per second. This momentum is generated by an impulse of $607/386 = 1.57$ pound-seconds.

Figure 3 gives a peak pressure at the steel wall of 507 pounds per square inch. The total outward radial force corresponding to this is $507 \times 2\pi 18$ or 57,300 pounds. The duration of the first peak indicated in Figure 3 is 70 microseconds. The area under the first peak gives the value of the impulse delivered to the wall by the pressure; approximately this is 2 pound-seconds.

Comparison of the pressure-gage record (2 pound-seconds) with the observed momentum imparted to the steel (1.57 pound-seconds) indicates fairly good agreement. In this the pressure-gage estimate comes out larger than the strain-gage estimate.

(b) The next case (Figure 5) deals with response of the same structure, a hoop section of the cylinder, to a different charge, about 15 grams of TNT detonated by a cap identical with that used alone in the previous case. The oscillogram shows a peak strain of 1.36×10^{-3} inch per inch. This is reached in 1.13×10^{-4} second (113 microseconds), so that the strain rate is 12.1 inches per inch per second.

Radial velocity is thus 218 inches per second; momentum of the steel is 5200 pounds mass-inch per second and impulse value is 13.5 pound-seconds.

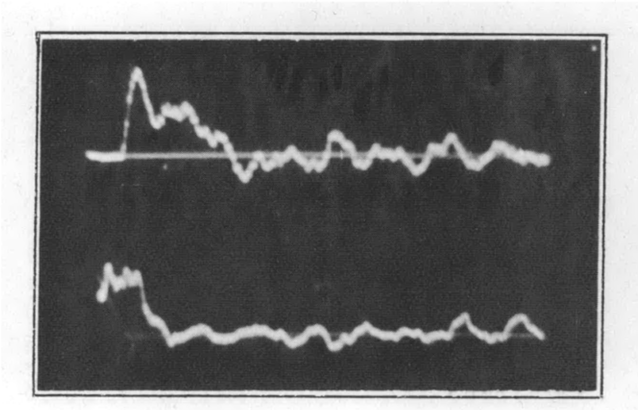

Figure 4a - Oscillogram

A natural frequency of about 2000 CPS may be seen. The initial rise of pressure (Figure 3) precedes the initial rise of stress (Figure 4) by an interval of more than 100 microseconds.

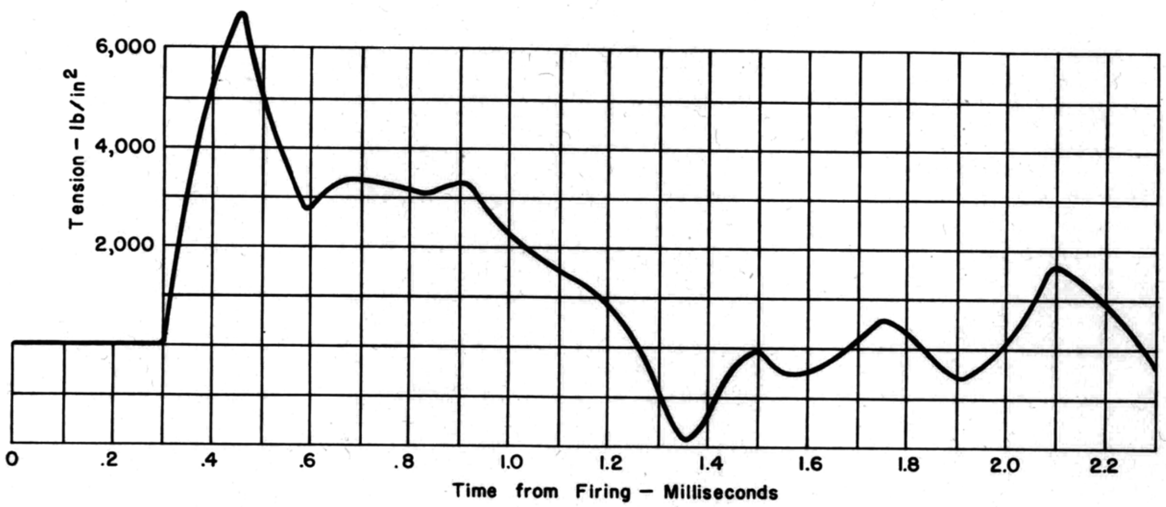

Figure 4b - Stress-Time Curve Traced from Figure 4a

Stress peak 6750 pounds per square inch. Strain peak 2.25 x 10-4 inch per inch. Duration of initial rise 160 microseconds.

Figure 4 - Hoop Stress at Equatorial Section of Tank

This stress was caused by pressure from the detonation explosion shown in Figure 3 and was measured by metalectric gage.

The pressure oscillogram for this case is not reproduced but it shows a peak of 17/18 x 2940 = 2780 pounds per square inch, and a duration of 50.7 microseconds. The area under the first pressure peak is 1/2 x 2780 x 2π x 18 x 50.7 x 10^{-6} = 8 pound-seconds. In this case the pressure-gage version of impulse (8 pound-seconds) is smaller than the strain-gage version (13.5 pound-seconds).

(c) The final case, Figure 6, to which this same process of calculation will be applied is that of the diaphragm at the bottom of the cylinder. In this case calculation of the momentum is a little more difficult. Considering a uniformly loaded circular plate clamped at the edge, the deflection at

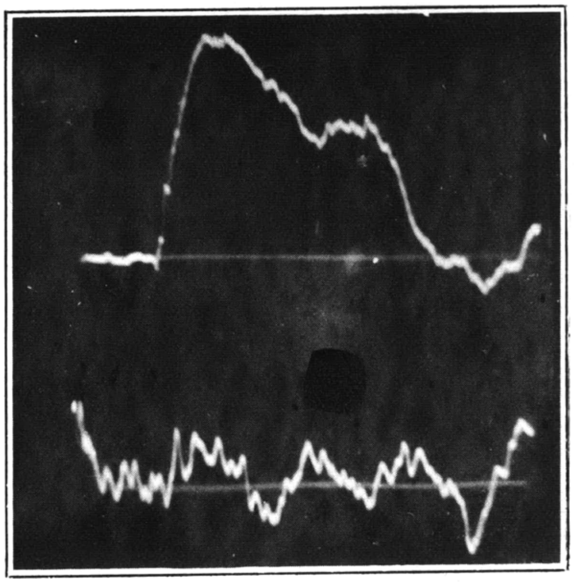

Figure 5a - Oscillogram

The time scale on the low-speed return sweep, shown in the lower curve, is about half that in the high-speed direct sweep in the upper curve. A natural frequency of about 1700 CPS may be seen.

The disturbances preceding the initial rise are not understood; they appear also in the pressure record.

An interval of less than 50 microseconds occurs between the initial rise of pressure (not shown) and the initial rise of stress.

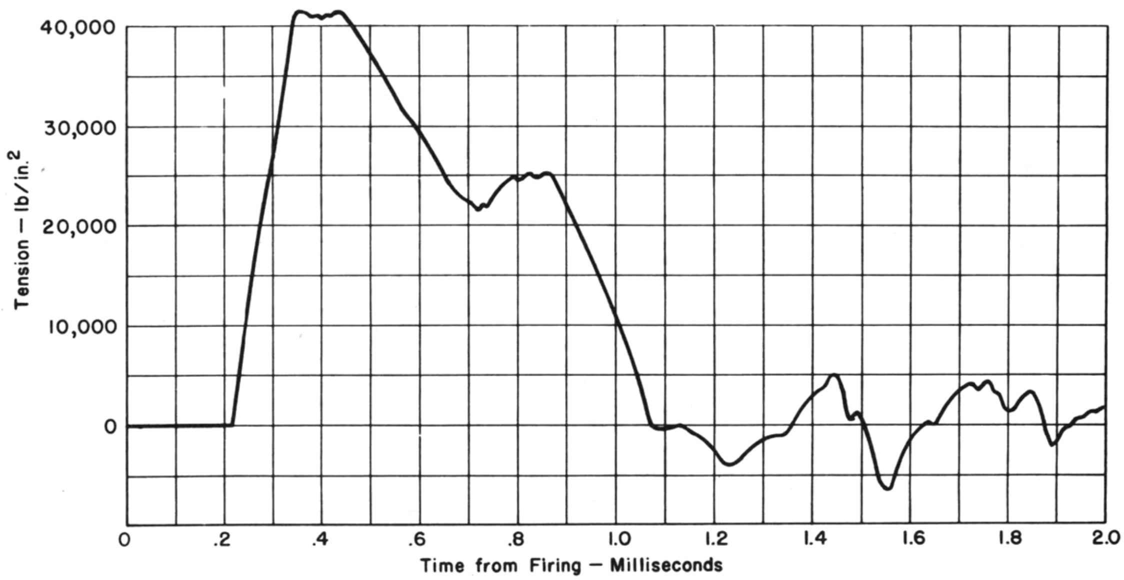

Figure 5b - Stress-Time Curve Traced from Figure 5a

Stress peak 40,800 pounds per square inch. Strain peak 13.6 x 10^{-4} inch per inch. Duration of initial rise 113 microseconds.

Figure 5 - Hoop Stress from 15 Grams of TNT at the Equatorial Section of the Tank

The pressure curve is not reproduced here.

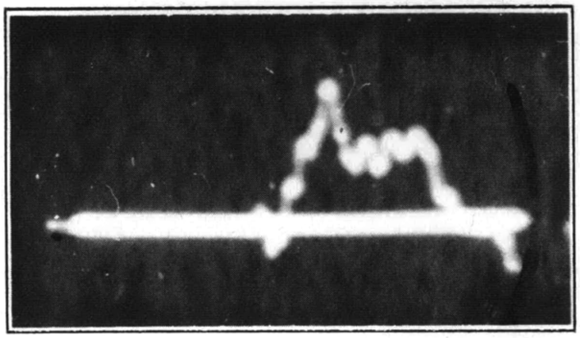

Figure 6a - Oscillogram

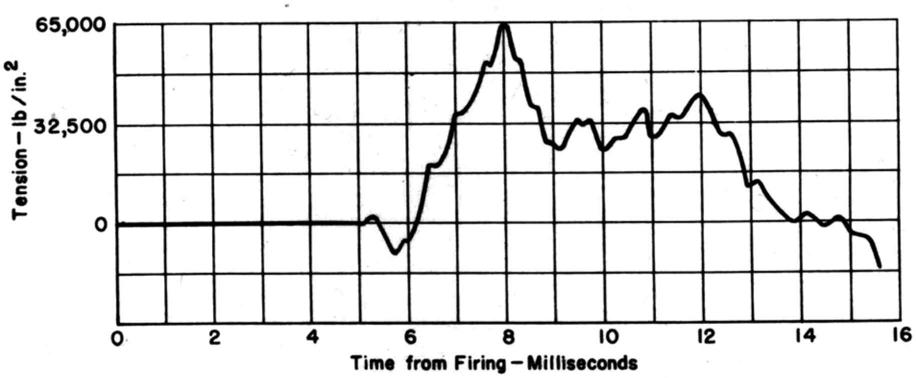

Figure 6b - Stress-Time Curve Traced from Curve 6a

Stress peak 65,000 pounds per square inch. Duration of initial rise 2.3 milliseconds.

Figure 6 - Drumhead Stress at Center of Diaphragm

This stress was caused by the pressure from a detonator explosion as shown in Figure 3.

the center is related to the stress at the center in the following manner

$$\delta_{max} = \frac{1 - m}{2} \frac{a^2}{h} \frac{\sigma_{max}}{E}$$

where δ_{max} is the maximum deflection at center of diaphragm

m is Poisson's ratio (0.3 for steel)

a is the outside radius of diaphragm

h is the thickness of diaphragm

σ_{max} is the maximum stress (radial or tangential) at center of diaphragm

E is Young's Modulus

$$\delta_{max} = \frac{0.7}{2} \frac{324}{0.375} \frac{65000}{30 \times 10^6} = 0.656 \text{ inch}$$

Assuming that the stresses and the deflections at the center increase together, this deflection was reached in 0.0023 second. Therefore, the velocity normal to the diaphragm at its center is

$$V_{max} = \frac{0.656 \text{ in}}{0.0023 \text{ sec}} = 285 \text{ inches per second}$$

Now, assuming that the initial normal velocities all over the diaphragm varied in the same manner as the normal deflections, and assuming that

$$\delta_r = \delta_{max} \left(1 - \frac{r^2}{a^2}\right)^2$$

then

$$V_r = V_{max} \left(1 - \frac{r^2}{a^2}\right)^2$$

These assumptions are very crude and need to be modified by further analysis, but they will serve to obtain values of initial momentum of the proper order of magnitude. The initial momentum

$$M = \frac{2\pi h\gamma\ V_{max}}{g} \int_0^a r\left(1 - \frac{r^2}{a^2}\right)^2 dr$$

where γ is the weight density of diaphragm material

g is the acceleration due to gravity

and the other symbols have the same meaning as before. The value of the integral for a = 18 inches is 54 square inches.

The numerical value of M is

$$M = \frac{2\pi \times 0.375 \times 0.283 \times 285 \times 54}{386} = 26.5 \text{ pound-seconds}$$

The impulse delivered to the diaphragm from the detonator may be calculated from the peak of pressure delivered to the center of the diaphragm, which is 506 pounds per square inch. This pressure is distributed in such a way over the diaphragm as to give an average value of 450 pounds per square inch. The area of the diaphragm is 1020 square inches. The total maximum force exerted is therefore 458,000 pounds. The area of the force-time curve is 1/2 x 458,000 pounds x 0.000070 second = 16 pound-seconds.

The results obtained are summarized in Table 1. For comparison with theoretical work, the impulse values are referred to unit area.

Agreement between the last two lines indicates correctness of the calibration of the pressure gage.

COMMENT

The results of these tests as analyzed are not intended to have more than a low precision. Both the observations and the calculations are subject to corrections which, if given the worst possible cast, might make the disparities much greater than they now appear. However, agreement between two versions of impulse, even though extending only to the order of magnitude, shows that pressures indicated by the gage have a certain degree of validity. So far as is known, this is a new result.

TABLE 1
Summary of Impulse Densities

	(a)	(b)	(c)
Responding System	Hoop	Hoop	Diaphragm
Area of System, inches^2	113	113	1020
Excitation	Detonator	15g TNT	Detonator
Distance from charge, inches	18	18	18
Impulse density lb-sec./in^2 by pressure gage (pressure x duration)	0.018	0.071	0.016
By strain gage (momentum imparted)	0.014	0.120	0.026

Possible sources of error include the effect of inertia of the water on response of the steel structure, which has been ignored in the calculations of momentum. This is justified on the ground that the transient action of the shock wave, in the brief interval considered, constitutes the entire action of the water on the steel.

Another point which has been suggested refers to the reaction on a solid boundary as affected by reflection of the wave. There is some ground for asserting that this reaction is double the pressure value found in the fluid at a distance from a solid boundary. At the same time the boundary is not in fact completely rigid, but subject to elastic deflection. In any case, such effects have been ignored in the calculations herein presented.

Further development is very actively proceeding, both as to improvement of the gage and refinement of the calibration process.

CONCLUSIONS

If at the present moment conclusions are necessary, those which appear to have the best chance of being right are as follows:

1. The shock wave exercises control of damage to steel structure from an underwater explosion.

2. In the shock wave, impulse, i.e., time integral of pressure, determines the damaging effect.

3. The pressure peak in the shock wave from an underwater explosion diminishes in proportion to the reciprocal of the radial distance from the center of the explosion.

4. The duration of the initial pressure peak changes little with increasing distance from the explosive center.

5. Impulse per unit area of the shock front diminishes with the reciprocal of the distance from the explosive center.

6. Impulse per unit area at a given distance from the explosive center increases with the 2/3 power* of the weight of charge.

7. Ignoring differences in chemical constitution of explosives, and combining the small scale results obtained at the David W. Taylor Model Basin with Hilliar's data* on large charges, impulse density, in pound-seconds per square inch, has the values shown in Table 2.

TABLE 2

Impulse Density

Observed Value I, lb-sec/in^2	Weight of Charge W, pounds	Radial Distance from Charge r, inches	$(W)^{\frac{2}{3}}$	$\frac{I}{W^{\frac{2}{3}}/r}$
0.43	1900	1110	154	3.1
0.54	1600	762	137	3.0
0.38	1000	900	100	3.4
0.33	820	828	88	3.1
0.22	300	360	45	1.8
0.10	0.033	18	0.103	1.75
0.016	0.002	18	0.016	2.25

For design purposes,

$$I = 3.0 \frac{W^{\frac{2}{3}}}{r}$$

* "Experiments on the Pressure Wave thrown out by Submarine Explosions," R.E. 142/19, by H. W. Hilliar, Department of Scientific Research and Experiment, England, June 1919.