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AN EXPLORATORY INVESTIGATION OF THE EFFECTS OF UNDERWATER LINE CHARGES ON SHIP PLATING

by

J. K. Fleming and R. E. Oliver

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STRUCTURAL MECHANICS LABORATORY
UNDERWATER EXPLOSIONS RESEARCH DIVISION
PORTSMOUTH, VIRGINIA

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NOTATION

A	Plate area
a	Effective plating size
d	Plating deflection
E	Total shock-wave energy incident on the plate
ℓ	Length of line charge
R	Charge standoff
R_0	Perpendicular distance between the center of plating and geometric center of the line charge
s	Coordinate of element ds
t	Plating thickness
W	Charge weight
w	Explosive weight per-unit-length of line charge
α	Angle between R and R_0 as shown in Figure 11
σ	Yield stress of plate

ABSTRACT

A series of tests employing Mk 8 Mod 2 flexible linear type demolition charges and 4-ft by 6-ft panels simulating a portion of the DD 692 Class hull structure was conducted to determine the hull-plate dishing produced by line charges. The test results are presented and a damage rule is derived for estimating the permanent dishing produced by line charges detonated underwater parallel to the ship plating.

ADMINISTRATIVE INFORMATION

The work described in this report was conducted as part of the Naval Ship Research and Development Center Independent Research Program, Subproject ZR 011 01 01.

INTRODUCTION

BACKGROUND

Line charges are often used in salvage work that requires the charges to be detonated underwater in close proximity to a ship.[1] Therefore, information is desired concerning the effects of line charges on ship hulls. Damage rules for estimating the hull dishing produced by compact explosive charges used underwater against submarines[2, 3] and surface ships[4] are available; but no comparable means are available for estimating permanent hull deformations resulting from line charges detonated underwater. Therefore, an exploratory study to determine these effects has been initiated.

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[1] References are listed on page 18.

OBJECTIVES

The objectives of this project were:

1. To investigate the response of air-backed steel panels representing ship hull plating to the loadings produced by line charges detonated parallel to the ship plating underwater; and
2. To derive a damage rule for estimating hull-plate dishing from such loadings.

TESTING

APPROACH

The Navy, at present, employs Mk 8 Mod 2 linear type charges in its salvage operations; therefore, this line charge was chosen for this investigation.[1] It consists of a 2-in.-diam, 25-ft-long rubber hose filled with 50 lb of a 70/30 mixture of Composition A–3 and aluminum powder.

Initially, free-water tests employing this charge were conducted to determine the shock-wave pressure histories produced by the line charges. Then tests with the line charge detonated at various distances from targets were conducted.

Panels representing 4-ft by 6-ft portions of the DD 692 Class hull structure were chosen for targets as representative of thin-skinned ship hulls. These panels, which included two longitudinals and four frames, were attached to a heavily stiffened, boxlike steel structure for testing.

The tests were conducted with the charge horizontal and parallel to the length of the vertically oriented hull structure. Its midlength was placed opposite the geometric center of the target. The charge depth was 10 ft, a depth typical for salvage work against destroyers. In such salvage applications, the charge will generally be placed on the sea bottom. The effect of the bottom is, however, small and varies depending on the consistency of the bottom material. The tests were, therefore, conducted in free water to assure well-defined test conditions.

Tests with cylindrical charges of a length-to-diameter ratio of 1:1 were included in the investigation to facilitate comparison of the line charge tests with damage estimating formulae previously derived for such compact charges.[4]

TARGET CONSTRUCTION

The test vehicle was fabricated from 1¼-in.-thick HY-80 plate. It was a 4-ft by 6-ft boxlike structure with 1¼-in.-thick HY-80 external bar-stiffeners. The test panels, which simulated a section of the DD 692 Class destroyer hull in way of Frames 34 and 35, were fabricated of ¼-in.-thick MS plate (average yield – 44,000 psi) stiffened with two longitudinals and four frames as shown in Figure 1. This figure also shows the strong edge support that is provided by the boxlike structure. Figure 2 shows a rear view of a panel mounted on the test vehicle. This photograph was taken after one of the tests.

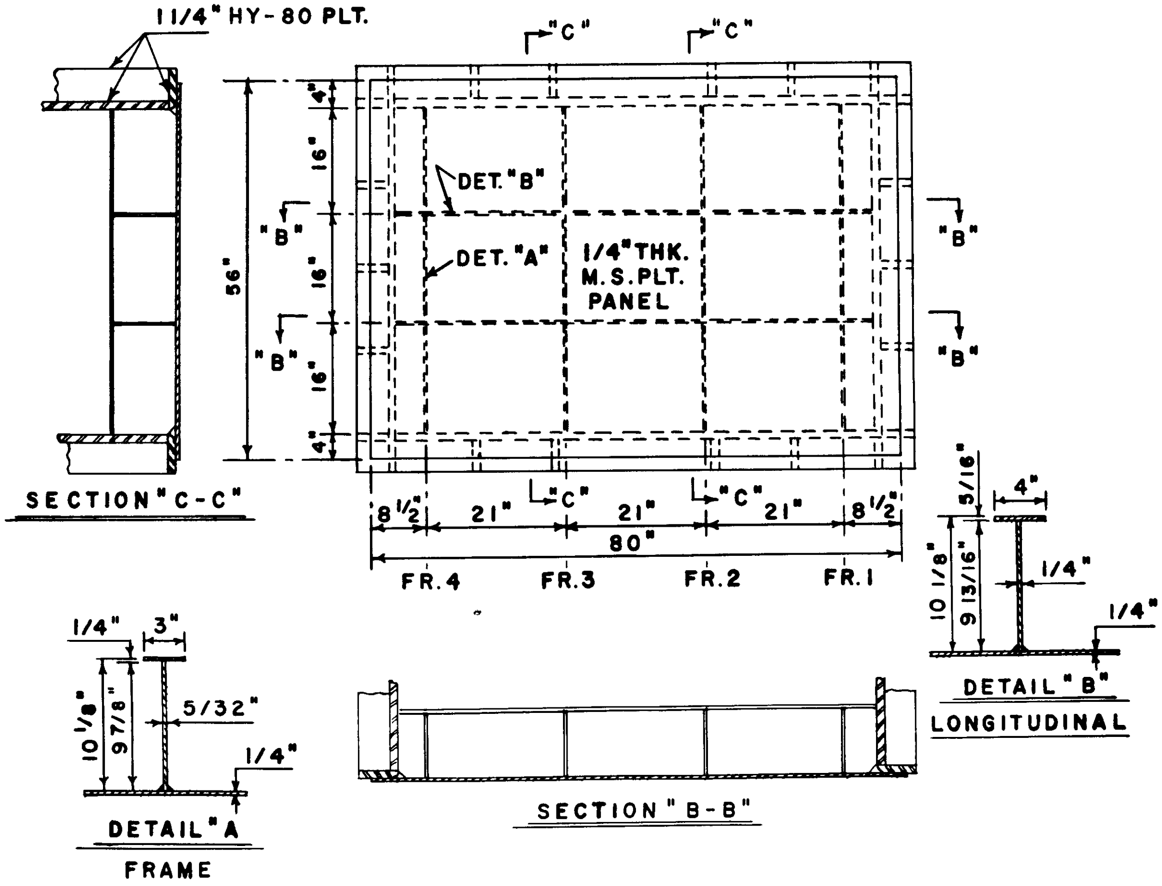

Figure 1 - Test Panel Details

INSTRUMENTATION

For the initial tests, pressure gauges (PE) were used for recording the free-water pressure measurements. For the panel tests, three mechanical deflection gauges (MD) were used to record the plating and stiffener deflections; in addition two PE gauges were installed at the center of the panel; one PE gauge was positioned 1½ ft in front of the panel and another one was 5 ft in front of the panel. Figure 3 shows the PE locations for one of the free-water tests and Figure 4 shows instrumentation locations for the panel tests.

Figure 2 - Test Panel Showing Frames and Longitudinals

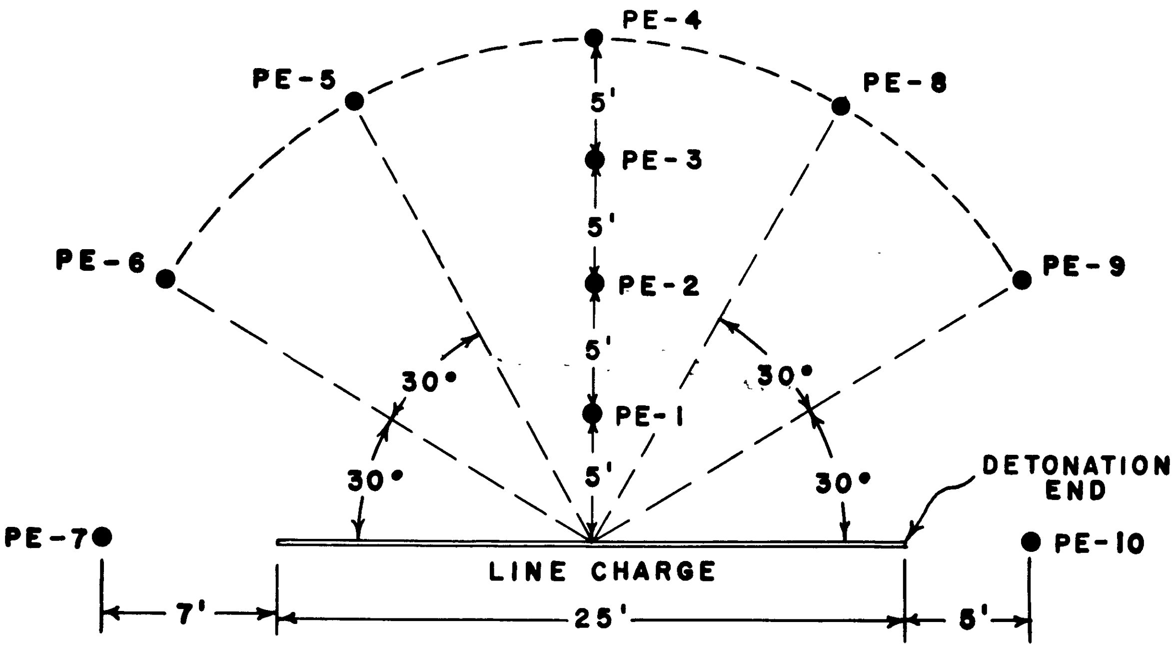

Figure 3 - A Schematic of Instrumentation for Free-Water Tests

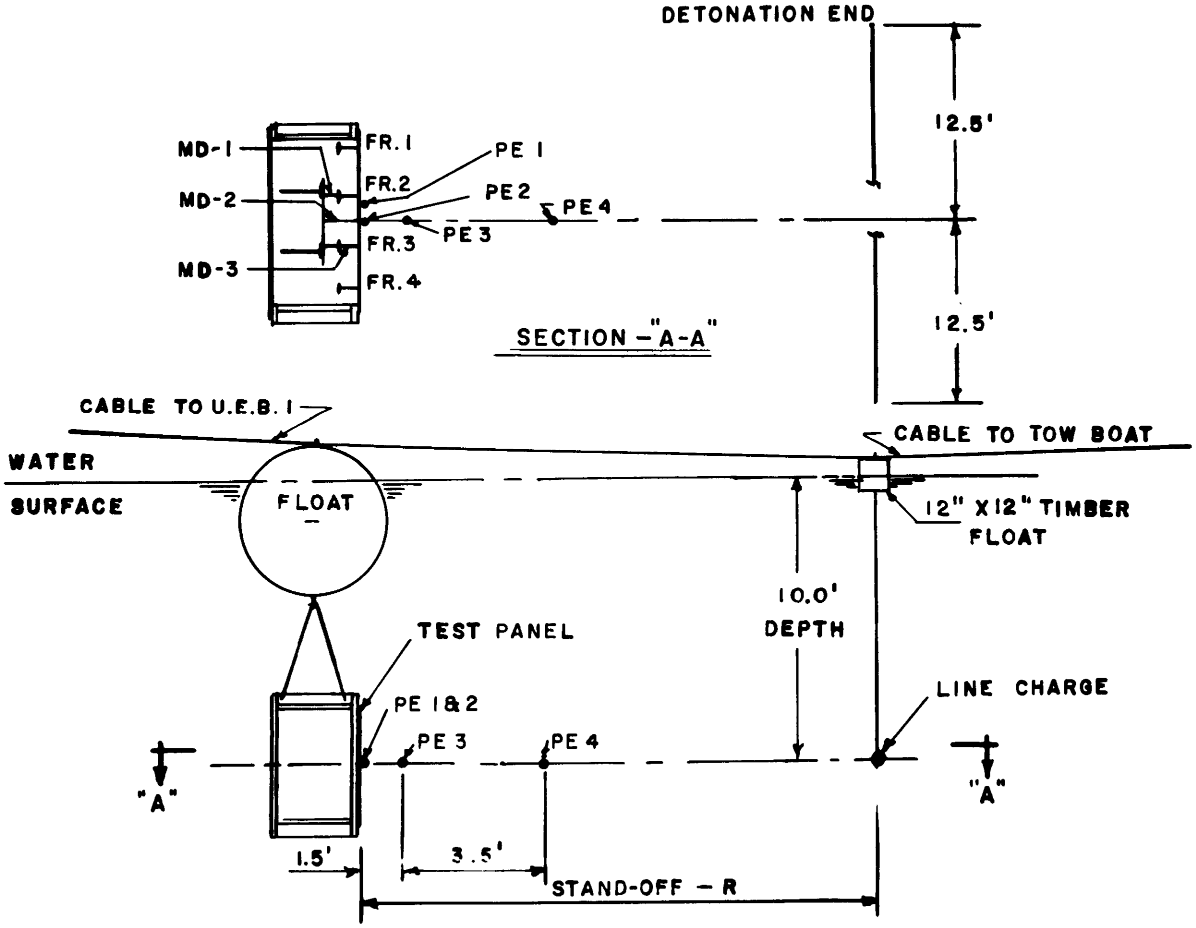

Figure 4 - Schematic of Instrumentation and Test Array for the Panel Tests

TEST CONDUCT

The tests were conducted in the Turning Basin of the Norfolk Naval Shipyard where the water depth is approximately 40 feet. The free-water pressure measurements were obtained by hanging the PE gauges, shown schematically in Figure 3, from a wooden float which also held the line charge.

The test vehicle was hung below a steel drum at a 10-ft depth during the tests. Figure 4 shows the test array. One of these panels that is ready for testing is shown in Figure 5. The pressure gauges are also shown in this figure: two gauges are at the center of the panel, one is 1½ ft and the other is 5 ft from the panel. Figure 6 shows a line charge supported by its float. The line charge was detonated from the end closest to Frame 1 of the test panel (Figure 4). Table 1 lists the pertinent data for all tests.

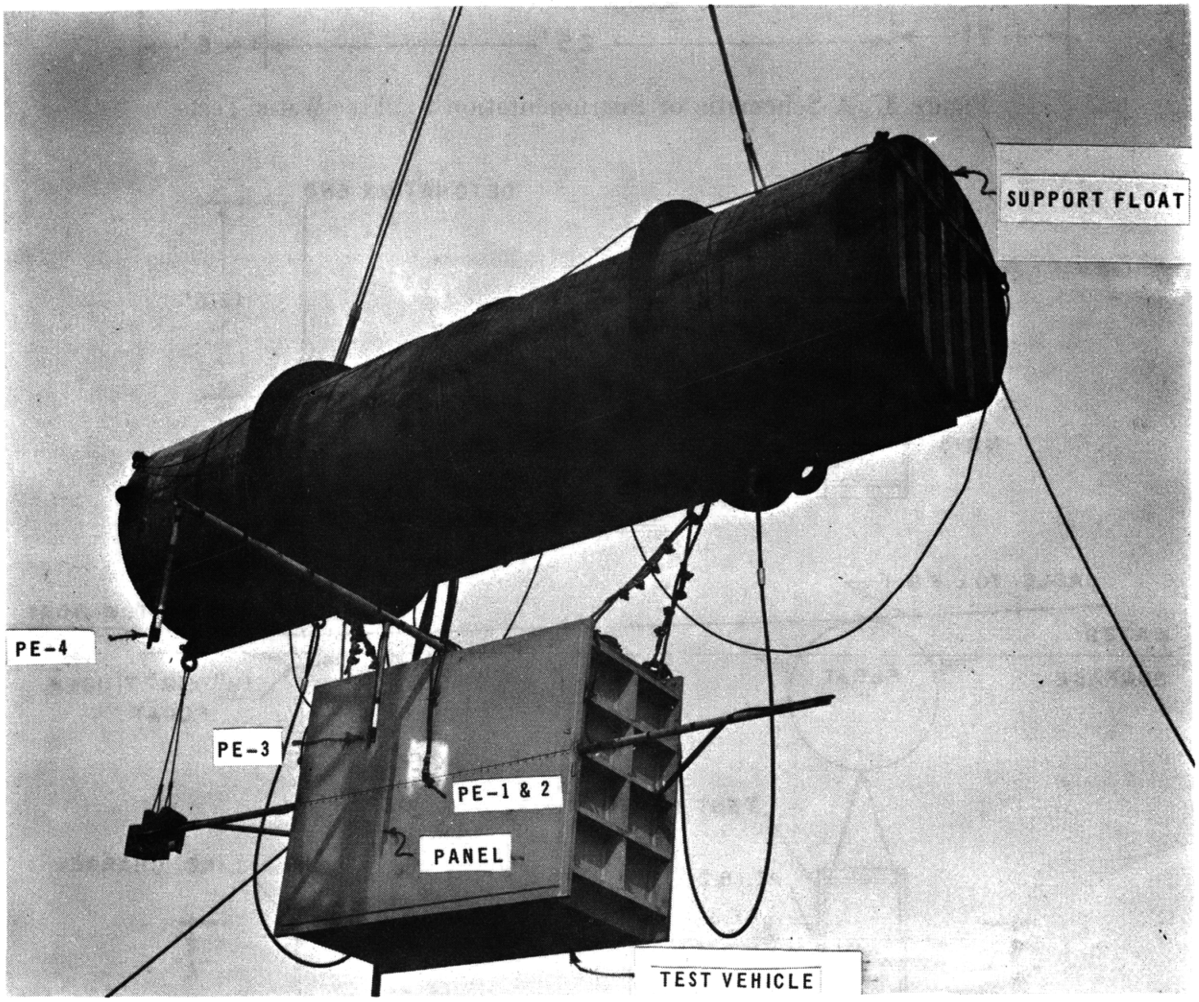

Figure 5 - Panel Rigged for Testing

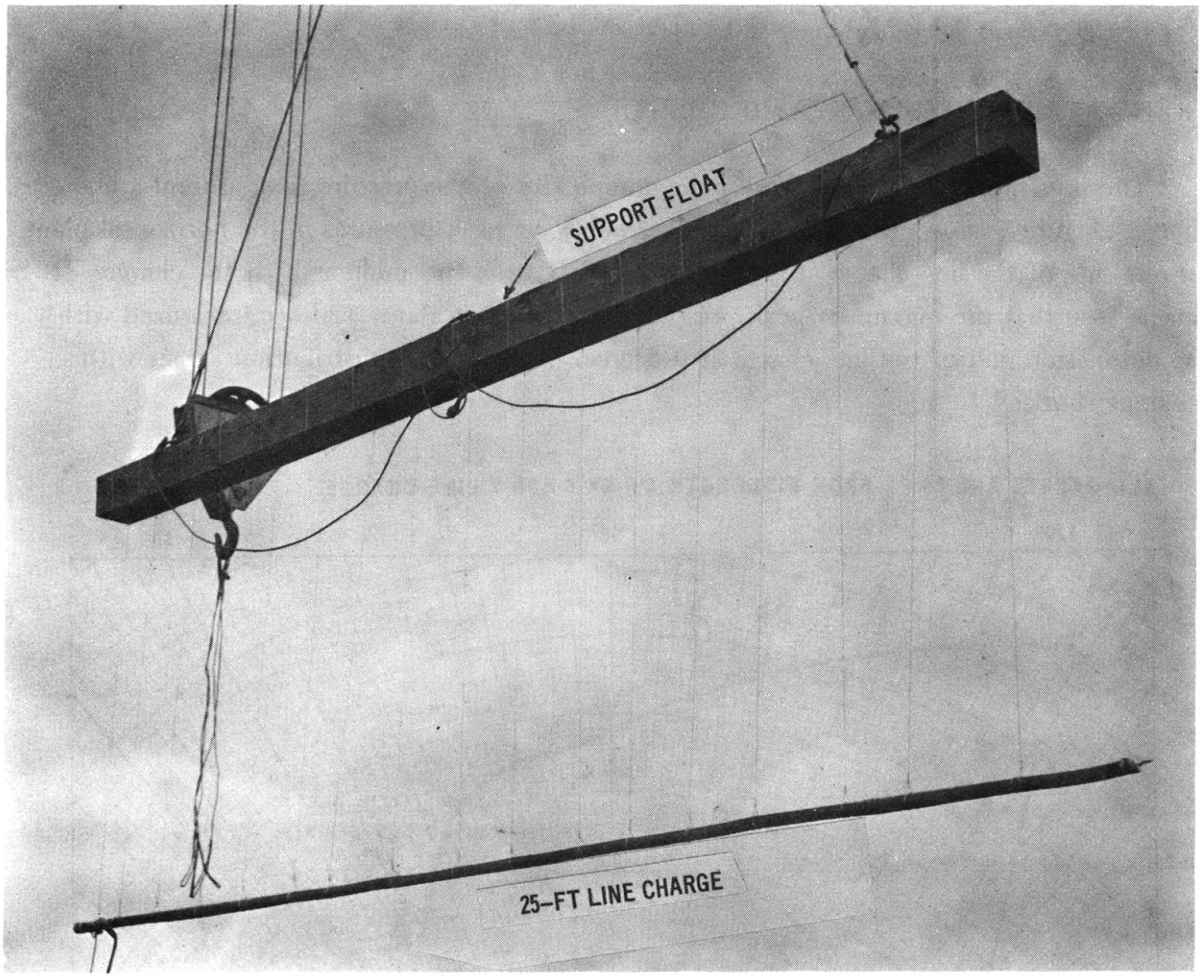

Figure 6 - Line Charge with Supporting Float

TABLE 1

Test Data

Test	Type of Charge	Charge Weight (lb)	Test Structure	Charge Depth (ft)	Minimum Standoff* (ft)	UERD Shot No.
Free-Water	Line**	50		10	–	7482
	Line**	50		10	–	7536
	Compact (HBX-1)	21		10	–	7538
Panel	Line**	50	Panel No. 1	10	30	7548
	Line**	50	Panel No. 2	10	40	7666
	Line**	50	Panel No. 3	10	50	7674
	Compact**	50	Panel No. 4	10	40	7696

*Standoff is measured normal to the panel from the geometric center of the charge.

**These charges were a 70/30 mixture of composition A–3 and aluminum powder. Line charges were Mk 8, Mod 2 Demolition Charges[1]; compact charges were cylindrical with a length-to-diameter ratio of 1:1.

FREE-WATER PRESSURE MEASUREMENTS

The pressure measurements reveal the complexity of the pressure field around a line charge. Figure 7 shows the distribution of shock-wave peak pressures in the horizontal plane on one side of the line charge at a standoff of 20 ft from the midlength of the charge. It can be seen that the maximum peak pressure is obtained at about 120 deg, measured with the detonation end of the line charge at 0 degree. This pressure distribution agrees with previous studies.[5-8]

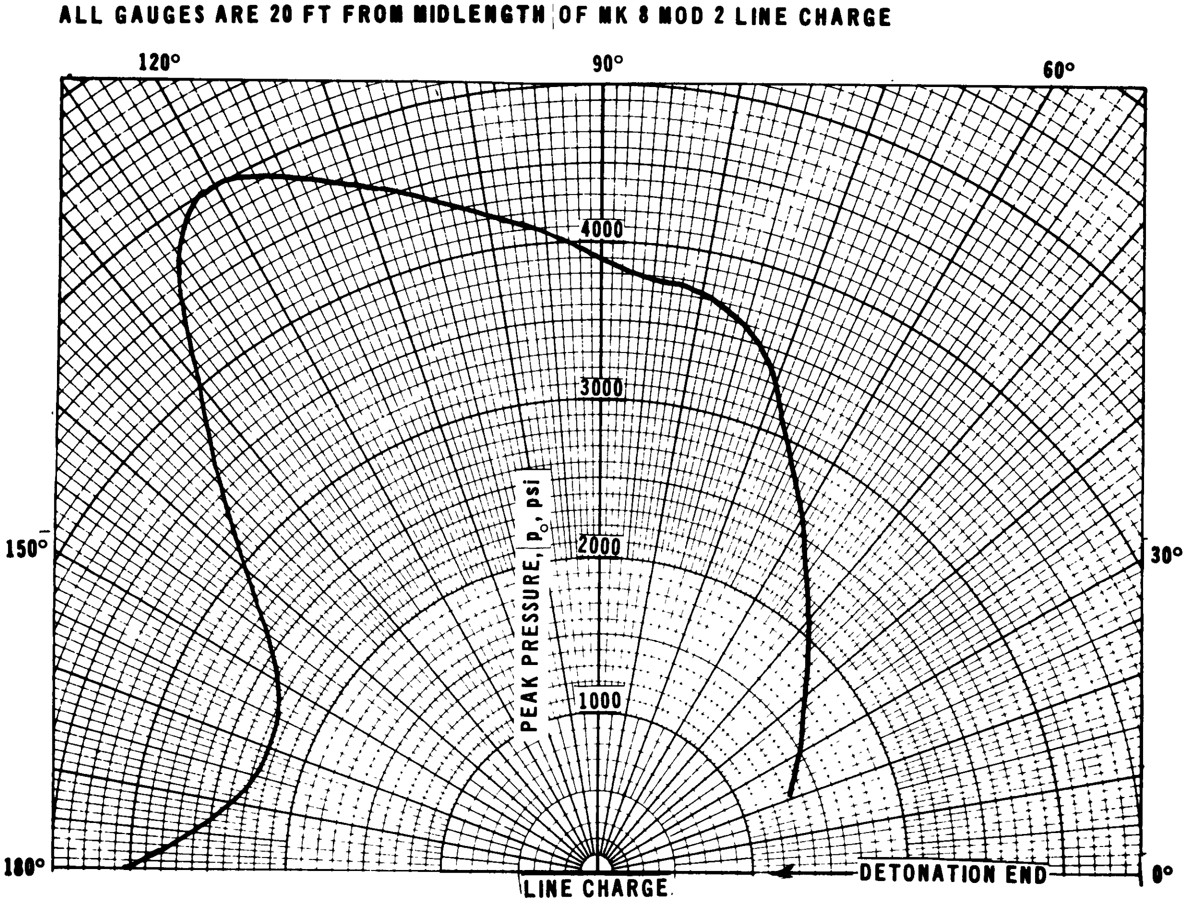

Figure 7 - Distribution of Peak Pressure around Line Charge

The pressure histories on the perpendicular bisector of the line charge resemble those of a compact charge; however, those taken at the same distance from the midlength of the charge but at an angle close to the detonation end have a lower peak pressure and a slower decay. Figure 8 shows this dependence on the angle with the charge. Figure 9 compares the line charge pressure signature on the perpendicular bisector with that of a compact charge, with the same explosive, total weight and standoff. It can be seen that the pressure histories are quite similar.

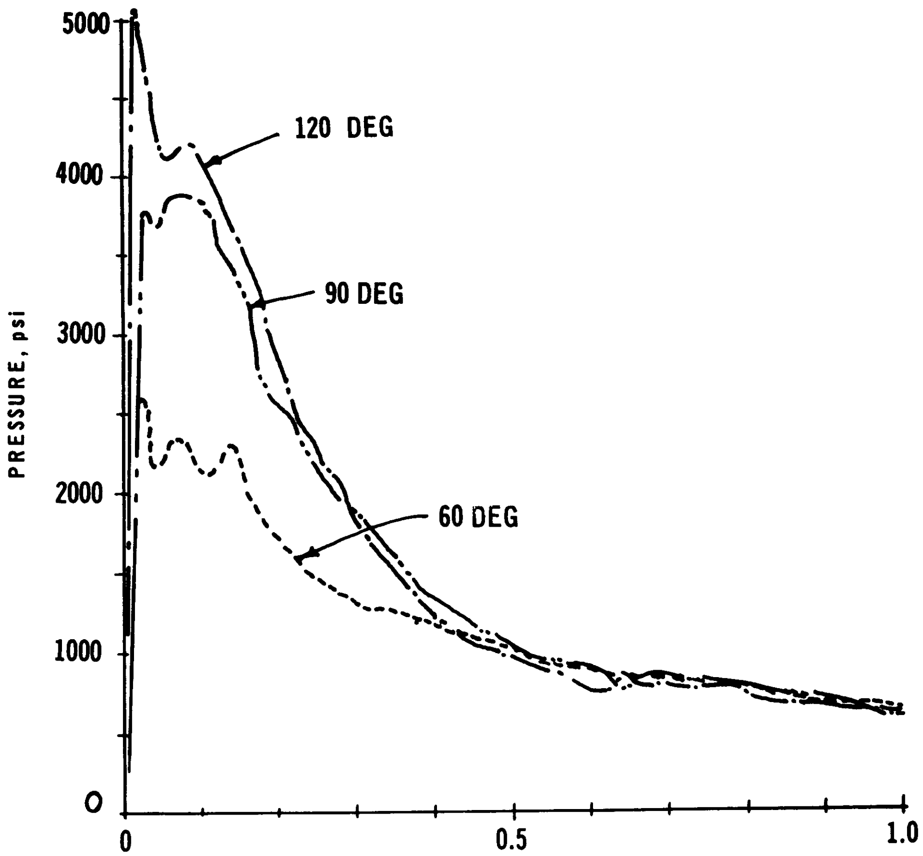

Figure 8 - Comparison of Shock Waves at Various Positions around Line Charge
(at 20-ft standoff from midlength of charge)

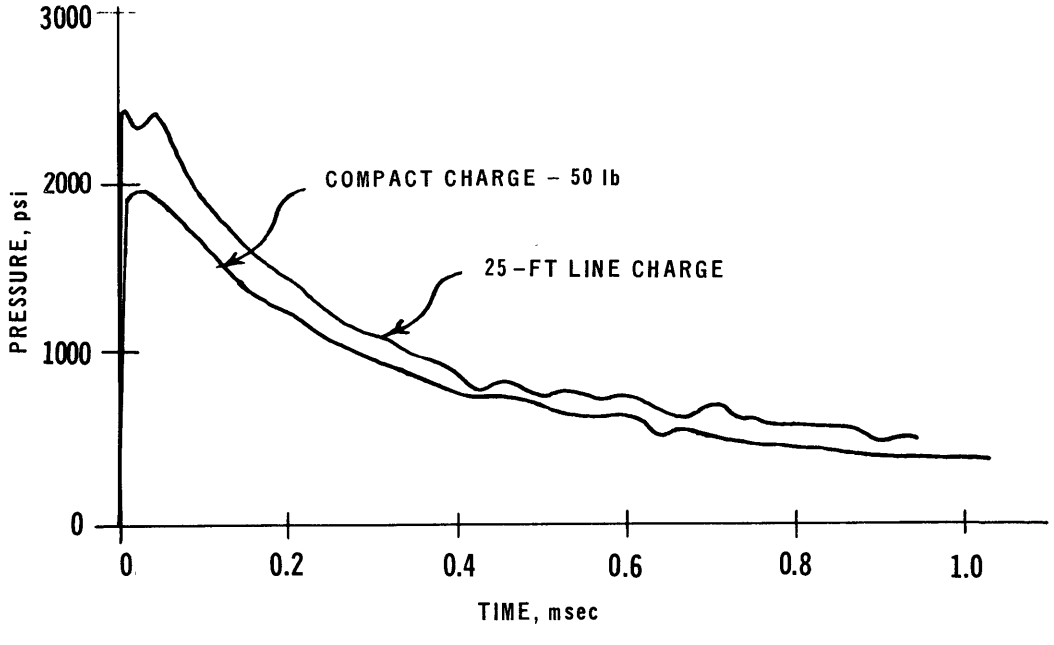

Figure 9 - Comparison of Line Charge and Compact Charge Pressure Histories
(at 35-ft standoff from gauge)

DAMAGE EFFECTS

In each of the panel tests the frames and longitudinals moved inward and the hull plating deflected inward between frames. Figure 10 shows one of the damaged panels after the 30-ft standoff line charge attack and Figure 2 shows the rear view of a damaged panel. This damage was typical of all tests. In no case was the hull plating fractured.

Table 2 lists all measured set deflections for the four panel tests. However, it should be pointed out that the deflection of the frames and longitudinals cannot be considered representative of damage produced in a ship hull because of the edge restraints provided by the boxlike structure. The following analysis will therefore be concerned only with the panel dishing relative to the adjacent strength members. Ordinarily the primary emphasis should be placed on the center panel which is farthest removed from the edge restraint provided by the boxlike structure. However, the deflection measurements did not show any systematic differences between the center panel and, therefore, all these measurements were considered in the analysis.

The deflection histories showed no bubble pulse action on the stiffeners but a small bubble pulse action on the panels between stiffeners. Since the bubble pulse contribution was insignificant in the range of the severer tests of primary interest, it will be ignored in the following analysis.

TABLE 2

Maximum Set Deflections in Inches

Panel No.	Charge Type	Standoff (ft)	Frame 1	Plating between Frames 1 and 2	Frame 2	Plating between Frames 2 and 3	Frame 3	Plating between Frames 3 and 4	Frame 4	UERD Shot No.
1	25-ft line	30	0.16	1.57	0.75	1.47	0.93	1.56	0.25	7548
2	25-ft line	40	0.10	0.93	0.32	0.94	0.25	0.69	0.06	7666
3	25-ft line	50	0.06	0.55	0.16	0.67	0.06	0.43	0.00	7674
4	compact	40	0.06	0.55	0.16	0.76	0.16	0.58	0.06	7696

Notes: 1. Compact charge was a cylindrical charge with length-to-diameter ratio of 1:1.
2. Measurements are accurate to ±0.05 inch.
3. All charge weights are 50 pounds.

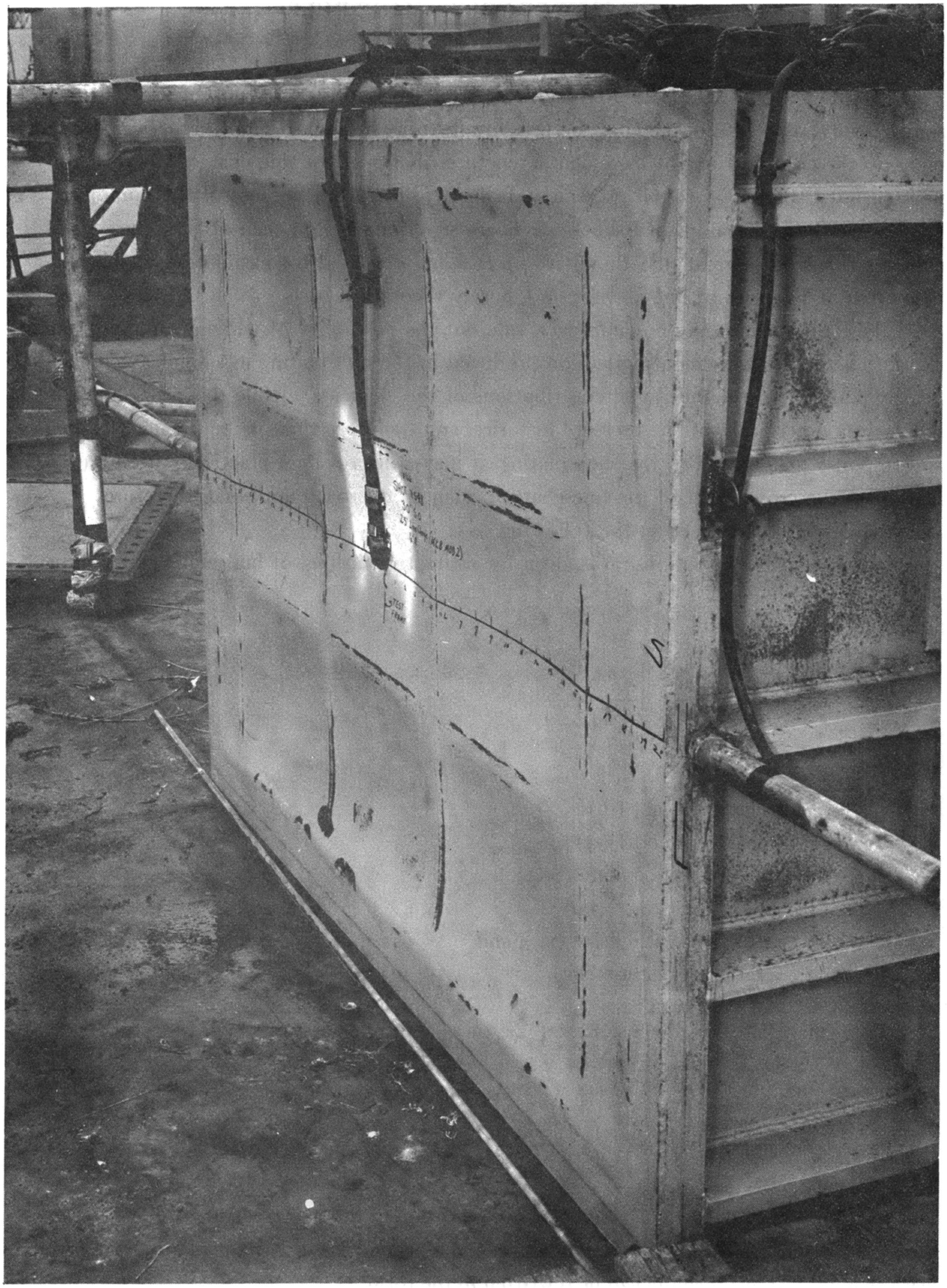

Figure 10 - Damaged Test Panel, Front View

DERIVATION OF THE DAMAGE RULE

The prediction of the pressure histories for line charges is extremely difficult. In a similar study[9] it was suggested that the pressure histories at a given point be derived by summing up the contributions of incremental length elements of the line charge, but this study pointed out that this process is extremely difficult to carry out because of the nonlinear manner in which the individual shock waves are superimposed on each other. These difficulties are indeed so great that they have up to now prevented the calculation of the pressure-time histories of line charges on a purely theoretical basis.

These difficulties may not, however, rule out the possibility of deriving an approximate expression for the permanent deflection produced in the hull plating in a similar manner, i.e., by considering the individual contributions of the elements. While this procedure cannot yield a description of the pressure histories, and therefore that of the detailed loading and response phenomena of the shell plating, it may still provide a practically useful approximation to the gross effect of the line charge. Such an approach appeared, therefore, worthwhile and is described in the following.

In Reference 4 a relationship is given for estimating dishing of hull plating by compact charges:

$$d = \mathit{const}\ \frac{a}{\sqrt{\sigma t}}\ \frac{\sqrt{W}}{R} \tag{1}$$

where W is charge weight (lb)
R is charge standoff (ft)
σ is yield stress of plate (psi)
t is plating thickness (in.)
a is effective plating size (in.), and
d is plating deflection (in.).

For rectangular plates of dimensions $2a_1\ 2a_2$, a is determined from:

$$\frac{1}{a^2} = \frac{16}{45}\left(\frac{1}{a_1^2} + \frac{1}{a_2^2}\right). \tag{2}$$

This relationship, Equation (1), gives a gross description of the damage, since it does not consider the finer points in the interaction between loading and the deforming plate. For a given plate shape the above formula can be rewritten in the form:

$$d = \frac{(const)}{\sqrt{\sigma t}} \frac{\sqrt{AW}}{R}$$

or

$$d = \frac{const}{\sqrt{\sigma t}} \sqrt{E} \qquad (3)$$

where A is the plate area, and
E is total shock-wave energy incident on the plate.

Let us now consider the line charge as consisting of elements of length *ds*. Then we may assume that the deflection of the shell plating between stiffeners can be correlated with the sum of the incremental shock-wave energies dE_S radiated from the line charge elements. Here we make the drastic assumption that dE_S is not affected by the shock waves from the other line charge elements as it propagates toward the shell plating.

For the line charge, we thus obtain

$$E = \sum dE_S$$

$$= const \int_{-\ell/2}^{\ell/2} A \cos a \frac{w\, ds}{R^2}$$

where w is explosive weight per-unit-length of line charge
ℓ is length of line charge
a, s and R are defined in Figure 11.

This expression can be rewritten as

$$E = const\, A\, w \int_{-\ell/2}^{\ell/2} \frac{R_0}{(R_0^2 + s^2)^{3/2}}\, ds$$

or

$$E = const \frac{2A\,w\ell}{R_0\,(4R_0^2 + \ell^2)^{1/2}} \tag{4}$$

where R_0 is the perpendicular distance between the center of the plating and the midlength of the line charge as shown in Figure 11. Substituting this expression for the energy in the formula for d, Equation (3), we obtain finally for the deflection produced by a line charge:

$$d = const \frac{a}{R_0\sqrt{\sigma t}} \left[\frac{2w\ell R_0}{(4R_0^2 + \ell^2)^{1/2}}\right]^{1/2} \tag{5}$$

This is the deflection which would be produced by an equivalent compact charge

$$W_e = \frac{2w\ell\,R_0}{(4R_0^2 + \ell^2)^{1/2}} \tag{6}$$

as can be seen by comparing Equation (1) with Equation (5).

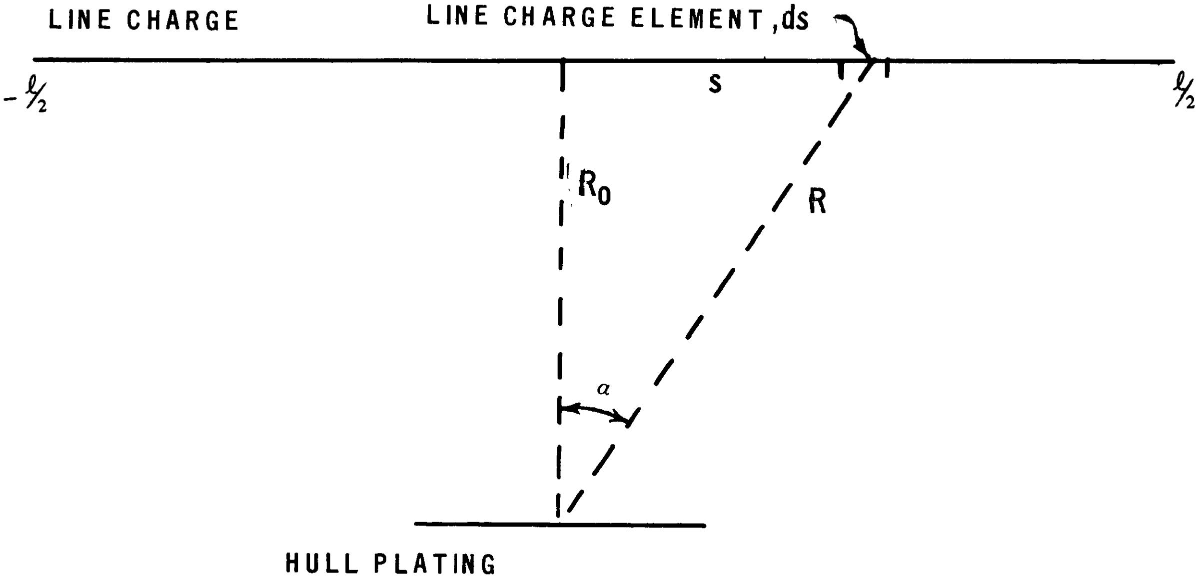

Figure 11 - Line Charge Configuration

In order to determine the proportionality constant in the expression for d, Equation (5), in these tests, Figure 12 was plotted. The deflections plotted represent the dishing of the plating relative to the adjacent stiffening members and were measured from straight lines joining adjacent frames. The straight line drawn in Figure 12 is the least squares best fit which passes through the origin. The standard deviation of the experimental values as expressed in

percent of the least squares values was found to be 20 percent. Therefore the deflection between stiffeners caused by a Mk 8 Mod 2 line charge can be approximately predicted by the equation:

$$d = 37 \frac{a}{R_O\sqrt{\sigma t}} \left[\frac{2w\ell\, R_O}{(4R_O^2 + \ell^2)^{1/2}} \right]^{1/2} \qquad (7)$$

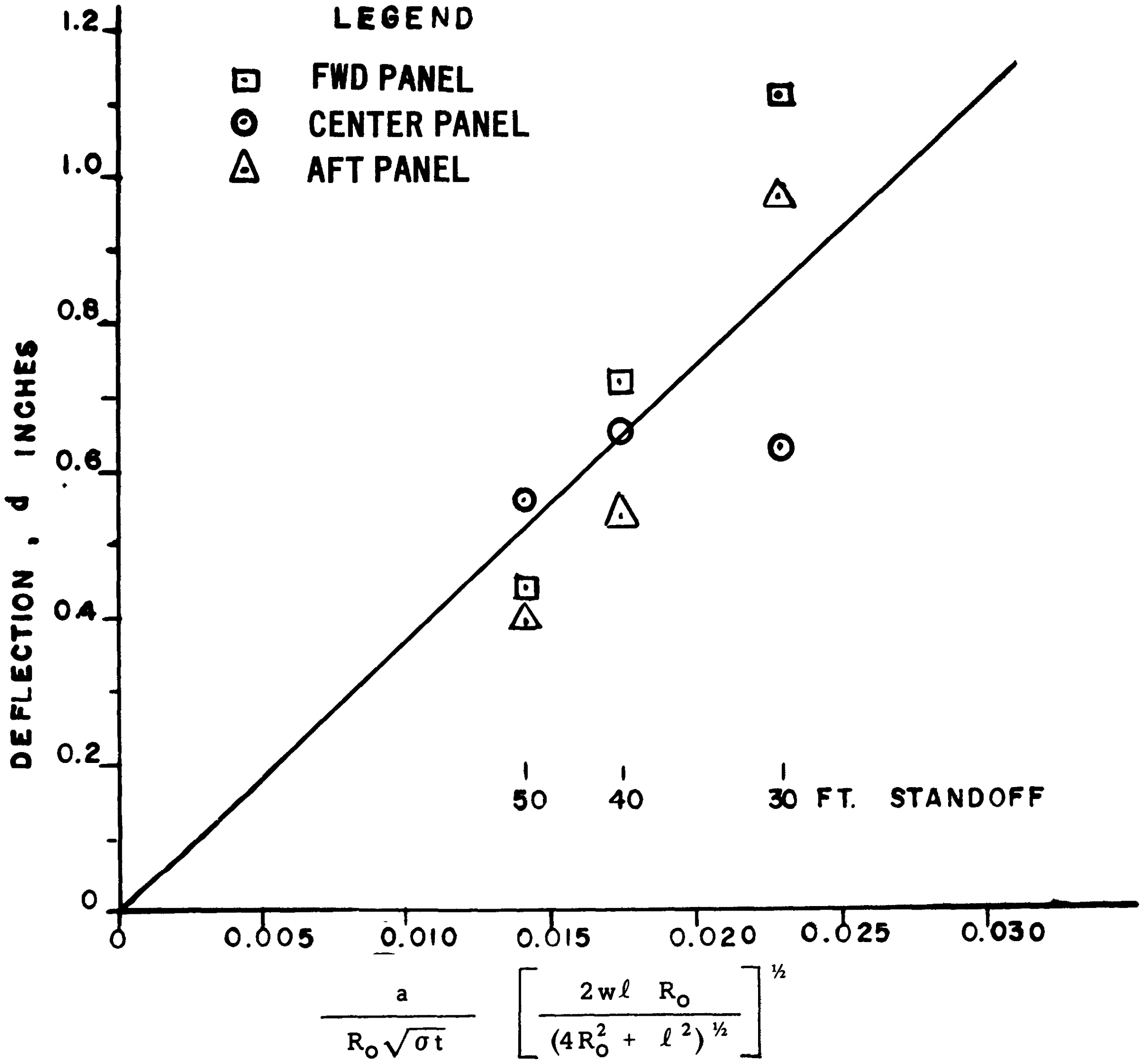

Figure 12 - Relationship of Deflection between Stiffeners

Figure 13 compares the measured experimental values with the prediction by means of a band that considers the standard deviation. This figure also shows experimental values for the panel test conducted with a 50-lb compact charge. It must be noted that this equation predicts only the deflection between frames and does not predict the frame deflection.

The experimental information obtained and the damage rule derived apply only to line charges suspended freely in water. However, in most salvage applications the line charges will normally rest on the sea bottom. The effect of the sea bottom on the damage produced will vary greatly with the bottom consistency but it is generally very small. The line charge may be slightly less effective on a soft mud bottom and somewhat more effective on a hard bottom. In extreme cases with very hard bottoms a conservative estimate may be obtained by increasing the charge weight by 35 percent.[10-12]

For applications of the line charges at depths considerably greater than 10 ft, increased damage might occur as the result of reloading and bubble pulse action.[4]

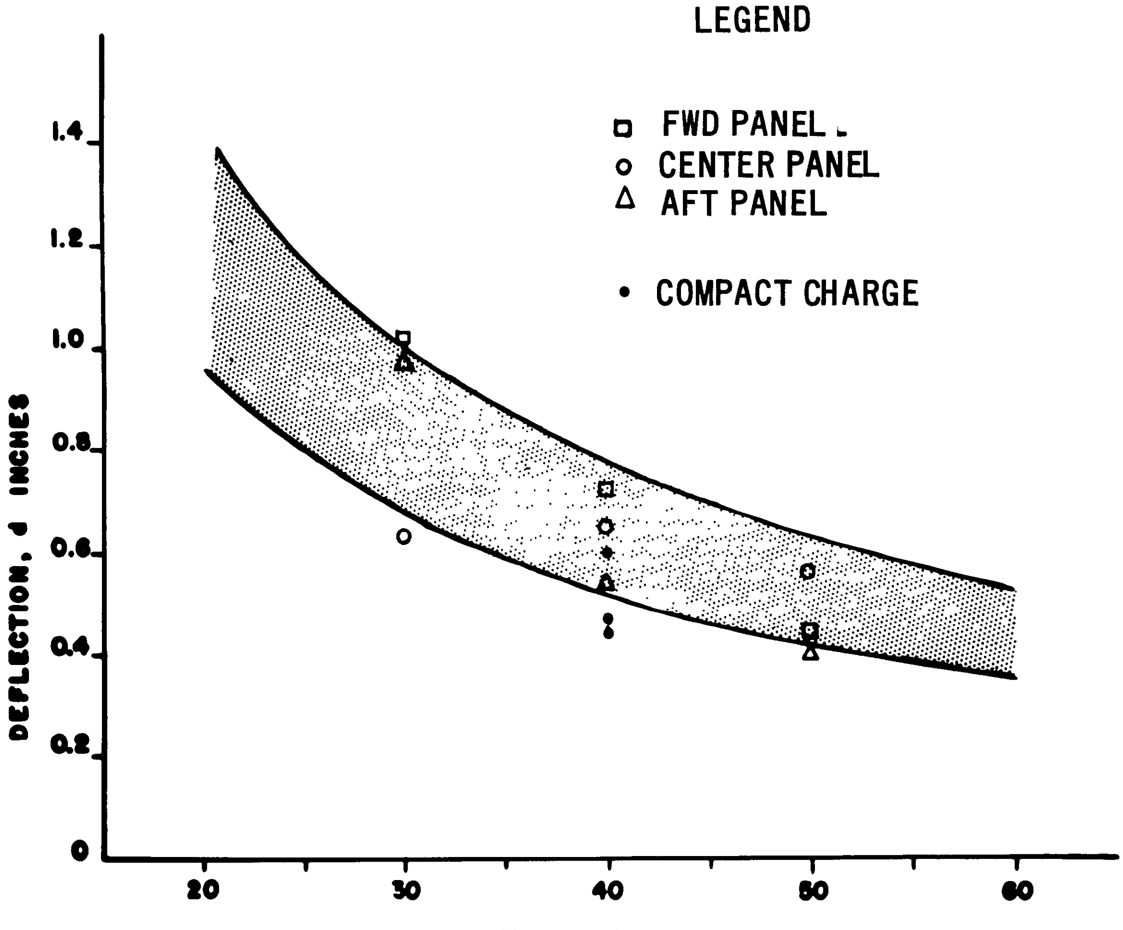

Figure 13 - Plating Deflection of DD 692 Class Destroyer Hull versus Mk 8 Mod 2 Line Charge Standoffs

(predicts only the deflection between frames)

SUMMARY

1. A series of tests with Mk 8 Mod 2 flexible linear type demolition charges was conducted against panels simulating a destroyer hull. The line charges, which were oriented parallel to the shell plating, produced up to about 1½-in. deflections in the severest test conducted.

2. The following conclusions apply to the damage range investigated:

a. The dishing of hull plating between adjacent stiffening members
produced by a line charge freely suspended in water can be
estimated from Equation (7).

$$d = 37 \frac{a}{R_o \sqrt{\sigma t}} \left[\frac{2w\ell \; R_o}{(4R_o^2 + \ell^2)^{1/2}} \right]^{1/2}$$

b. The standard deviation of the measurements was 20 percent.

3. The effect of the sea bottom on the damage produced by a line charge placed on the bottom will vary with the type of bottom but is generally quite small. A conservative estimate of the most severe bottom effect on the damage produced by a very hard bottom may be obtained by increasing the charge weight w in the damage rule by 35 percent.

REFERENCES

1. "Demolition Materials," Bureau of Naval Weapons Publication, NAVWEPS OP 2212 (Feb 1962) UNCLASSIFIED.

2. Fleming, J. K. et al., "The Effect of Small Charges on Submarine Hulls (U)," David Taylor Model Basin Report C-1307 (Jul 1962) CONFIDENTIAL.

3. Parnell, U. C., "The Resistance of Submarine Hulls to Underwater Explosions (U)," David Taylor Model Basin Report C-1900 (Jun 1965) CONFIDENTIAL.

4. Keil, A. H., "The Response of Ships to Underwater Explosions," David Taylor Model Basin Report 1576 (Nov 1961) UNCLASSIFIED.

5. Singletary, J. F. et al., "Line Charge Directivity," Naval Ordnance Laboratory, White Oak, Report NOLTR 65-182 (Nov 1965) UNCLASSIFIED.

6. Lemmis, T., "Directivity Patterns of Line Charges of Various Lengths and Fixed Weight (U)," Naval Underwater Ordnance Station, Newport,Report No. TM No. 345 (May 1965) CONFIDENTIAL.

7. Bayer, T. H., "End Fired Line Charge Measurements," Daystrom, Inc. Electric Division Test Report (Contract N140(122)74440B, Task 7) (Mar 1964) UNCLASSIFIED.

8. Coles, J. S. et al., "Shock-Wave Parameters Measured Off the Ends and Perpendicular Bisector of Line Charges 25 Ft. Long Containing 50 Lb. of Flexed TNT," Bureau of Ordnance Publication, NAVORD Report 102-46 (Jul 1947) UNCLASSIFIED.

9. Thompson, Philip A., "Prediction of Shock Waves from Tapered Charges (U)," David Taylor Model Basin Report C-1302 (Oct 1961) CONFIDENTIAL.

10. Cole, R. H., "Underwater Explosions," Princeton University Press, New Jersey (1948) UNCLASSIFIED.

11. Kennard, E. H., "Underwater Explosions A Summary of Results," David Taylor Model Basin Report C-334 (Feb 1951) CONFIDENTIAL.

12. Murray, W. W. and Walker, R. R., "Explosive Testing of Acoustic Mine-Sweeping Devices," Underwater Explosions Research Division Report 6-56 (Jun 1956) CONFIDENTIAL.

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13 ABSTRACT

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14 KEY WORDS	LINK A		LINK B		LINK C	
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