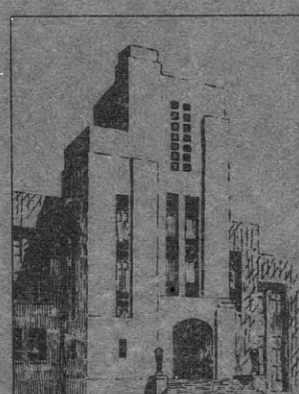
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

MODEL TESTS OF COMPOSITE STRUCTURES TO RESIST UNDERWATER EXPLOSION

BY COMDR. J. S. PARKINSON, USNR, AND CAPT. W. P. ROOP, USN



[redacted]

85

MARCH 1945 REPORT 491

NAVY DEPARTMENT

DAVID TAYLOR MODEL BASIN

WASHINGTON, D.C.

CONFIDENTIAL

REPORT 491

MODEL TESTS OF COMPOSITE STRUCTURES TO RESIST UNDERWATER EXPLOSION

BY COMDR. J.S. PARKINSON, USNR, AND CAPT. W.P. ROOP, USN

MARCH 1945

PERSONNEL

The work described here was carried on over a period of several years by many members of the Structural Mechanics Section, under the general supervision of Commander J.S. Parkinson, USNR, and Mr. G.H. Curl.

The report is basically the work of Commander Parkinson, with contributions by Captain W.P. Roop, USN, and Mr. Curl. Final checking of the tables was performed by Mr. Curl.

The method of determining merit factors by averaging analysis, as well as Appendices 1 and 2, were prepared by Captain Roop.

The digest was written by Captain H.E. Saunders, USN, who also made important contributions to the detailed presentation.

DIGEST*

INTRODUCTION

In 1940 a novel system of explosion protection for the underwater bodies of vessels was proposed to the Bureau of Ships, in part to supplement and in part to replace the multiple-bulkhead system developed during the preceding 40 years. A diagram of the latter system is given in Figure 2.

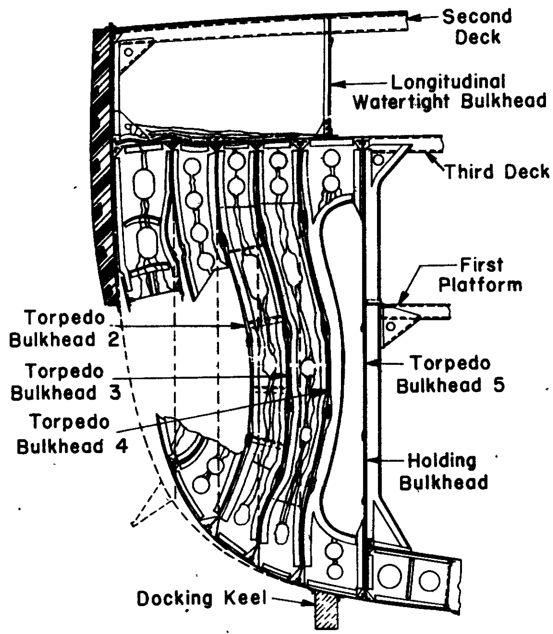


Figure 2 - Diagram Illustrating Underwater Explosion Damage to the Protective Structure of a Capital Ship

Provided the holding bulkhead remains intact, severe damage to the outer layers of the protective structure does not endanger the ship.

If most of the space between the protective layers is filled with oil or water before the damage occurs, the increase in flooding is small.

In a protective structure of this kind, the destructive energy which reaches it from the explosion undergoes three types of transformation. Some of the energy is dissipated in the form of heat or mechanical work on the protective structure, some is reflected back into the water, and some is transmitted to other parts of the larger ship structure. If actual rupture occurs in the material of the protective assembly, this is considered a type of mechanical work.

The proposed new system of protection attempted to take advantage of the dynamical characteristics of the underwater explosion by the use of a theory which had proved beneficial in similar fields elsewhere, particularly in acoustics. From this point of view the time constants of the structure

---

* This digest is a condensation of the text of the report, containing a description of all essential features and giving the principal results. It is prepared and included for the benefit of those who cannot spare the time to read the whole report.

and the time constants of the explosion are conceived to be the essential variables.*

The authors of this system, W.L. Bond and W.P. Mason of the Bell Telephone Laboratories, proposed (1) (2) (3)** that mechanical impedance and filter theory be applied to the design of explosion protection shields. Evidence from small-scale experiments made by them indicated that a more effective shield could be obtained by incorporating an attenuating medium such as sand in the outside layer of the protective structure than by using metal alone. In essence, the proposal contemplated a construction having a natural period of oscillation so long that the energy from the very brief explosion wave could readily be stored elastically in the structure and returned to the water later.

This report presents the results of a series of small-scale experiments undertaken by the David Taylor Model Basin at the request of the Bureau of Ships (4) (5) to examine the merit of the proposal made by Bond and Mason.

Since there was some uncertainty in the application of the mechanical filter theory to the particular protective assembly proposed, a number of other composite protective structures were developed by the Taylor Model Basin and tested in an effort to achieve the same type of action.† The fundamental idea behind all these schemes, of course, was to find some material or combination of materials capable of dissipating or reflecting more energy for a given deflection and for a given weight than shipbuilding steel.

TEST APPARATUS

The test setup used by the Taylor Model Basin was, in many respects, quite different from that of Bond and Mason and from the actual ship installation. For this reason the entire series of experiments is regarded as being purely comparative; no attempt is made throughout this report to draw conclusions from them in terms of absolute quantities.

The general procedure in the Taylor Model Basin experiments was to test a simple steel structure as a reference or control structure in the bottom of an open tank, as shown in Figure 4, and then to examine the effect of various protective structures in front of, or in combination with, the steel. It is believed that the trends indicated in these experiments can probably be

---

* Some phases of this theory have recently been discussed in TMB Reports 481 and 507 on the effect of impact on a simple elastic structure.

** Numbers in parentheses indicate references on page 85 of this report.

† The reasons for this are discussed in subsequent sections, and the structures are shown by diagrams in Tables 4, 5, and 6 on pages 33 to 37.

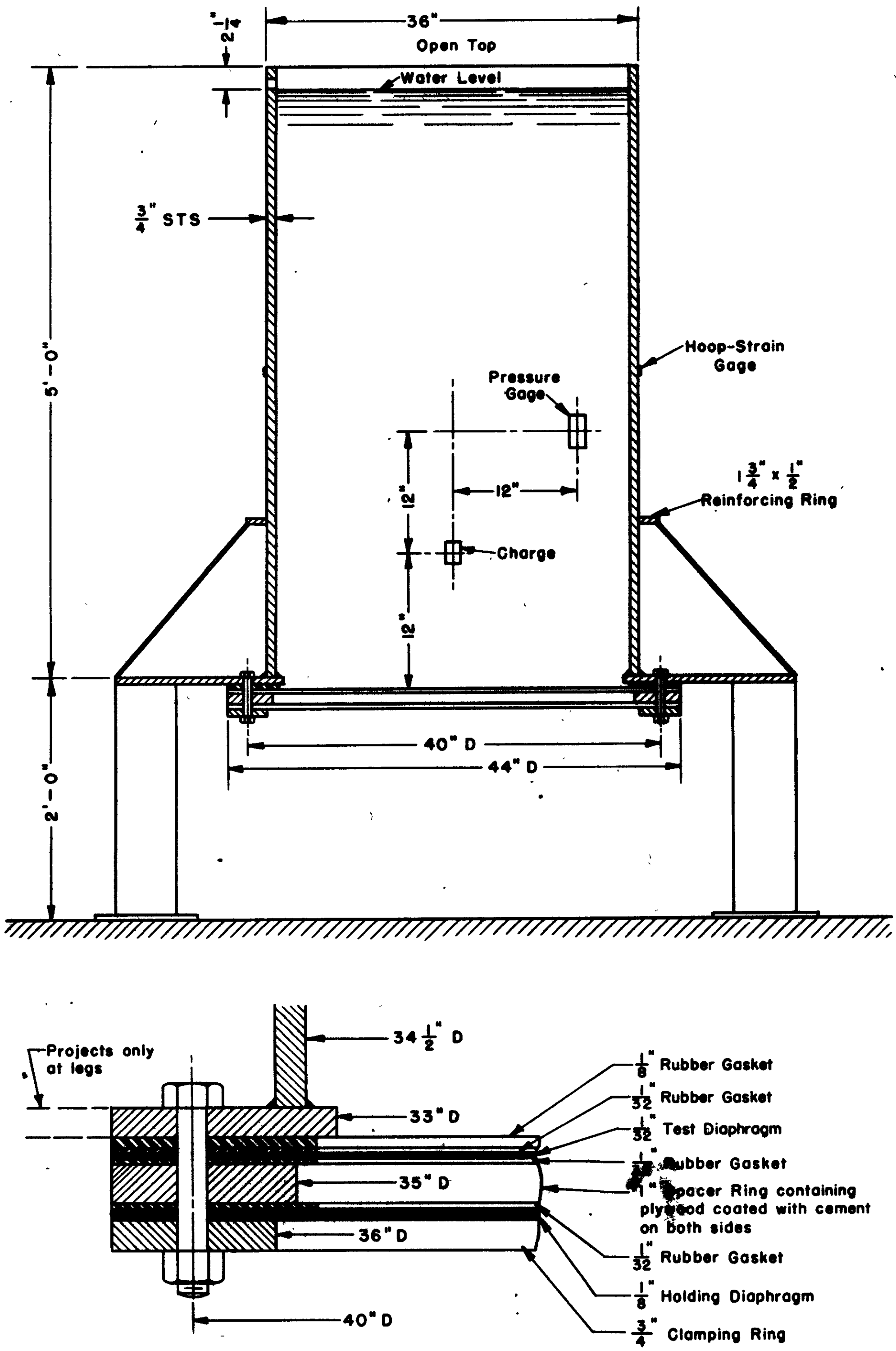


Figure 4 - Tripod Tank and Typical Test Assembly

The upper diagram is drawn to scale, and the positions of the charge and the gages apply to non-contact shots. The details of the typical protective assembly are for Test BL which was tested with 2 contact charges.

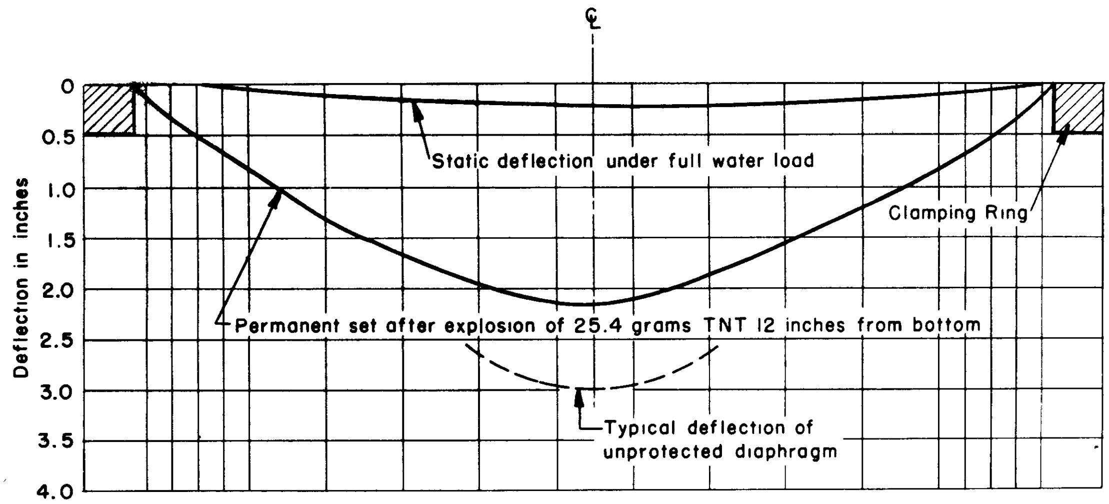


Figure 11 - Permanent Deflection Curve for Backing Diaphragm of Test R-1

The details of construction of this assembly appear in Table 4 on page 33. The shape is typical for a non-contact attack.

used in designing larger-scale model structures. Figures of merit have been developed, but they are still entirely comparative.

The thin circular diaphragm adopted for these early tests lent itself remarkably well to use as a sort of damage gage. It was not only easily fabricated and assembled, but its deformation could easily be measured after the explosion, as illustrated in Figure 11. Moreover, the amount of energy absorbed by it could be estimated by a consideration of the increase in area of the diaphragm inside the supports* and by a knowledge of its thickness and the yield strength of the material.

More than 120 protective assemblies were tested. Although various methods of measurement were used, interest, in general, centered on the deformation and the residual increase in area of the diaphragms caused by the explosion, and on the weight of the whole assembly. The effectiveness of the screen was gaged by the amount of energy absorbed by the screen and thus prevented from reaching and deforming the backing diaphragm. The manner in which the absorbed energy was estimated is explained subsequently in the report.

---

* If the diaphragm assumes a spherical shape after the explosion, the increase in area $\Delta A = \pi(\Delta Z)^2$, where ΔZ is the increase in center deflection due to the explosion; see Appendix 4. However, this formula was not used in calculating ΔA for these tests because the final shape was not exactly spherical.

TEST PROCEDURE

REFERENCE DIAPHRAGMS

To permit comparison between the performance of composite structures of various types and of simple steel diaphragms, a considerable number of tests were made with single steel diaphragms of thickness varying from 1/16 inch to 3/8 inch. The heaviest single diaphragms had a weight per square inch of exposed area approximately equal to that of the heaviest composite structures.

POSITION OF CHARGES

Since the purpose of the project was to investigate structures suitable for protection against contact explosions as well as near misses, experiments were made with the test charge in contact with the structure as well as 12 inches above it. It had been supposed that a charge in contact with the structure would do more damage than a similar charge at a distance of 12 inches. For this reason 1/2-ounce charges were used for the contact explosions instead of the 1-ounce charges which were normally used for non-contact shots.

MULTIPLE SHOTS

It was found in a number of preliminary tests in this series that the diaphragms had by no means reached the rupture point after a single charge had been fired at them. To take advantage of this, the backing diaphragms were carefully measured after the first shot, and second shots were then fired, after which the diaphragms were again measured.

It was thus possible to obtain a second set of data on each plate or assembly with no more trouble than to reset the instruments and insert another charge in the tank. In some cases more than two charges were fired in order to increase the ultimate damage.

TEST RESULTS

The irregular contour of the backing diaphragms under the static water load in the tank, such as appears in Figure 11, may be due to irregularities in the material, to irregularities in the filling materials of the composite assemblies, or to difficulties in making up the composite assemblies.

Commercial rolled sheet steel, both black and galvanized, such as was used for many of the parts in these tests, is notoriously irregular in characteristics and behavior. It is known, for instance, that black steel sheet will not roll up into a smooth and uniform cylinder of reasonably small radius. The regions of localized strain shown in Figure 12 indicate that something of the kind may be responsible for irregular behavior here.

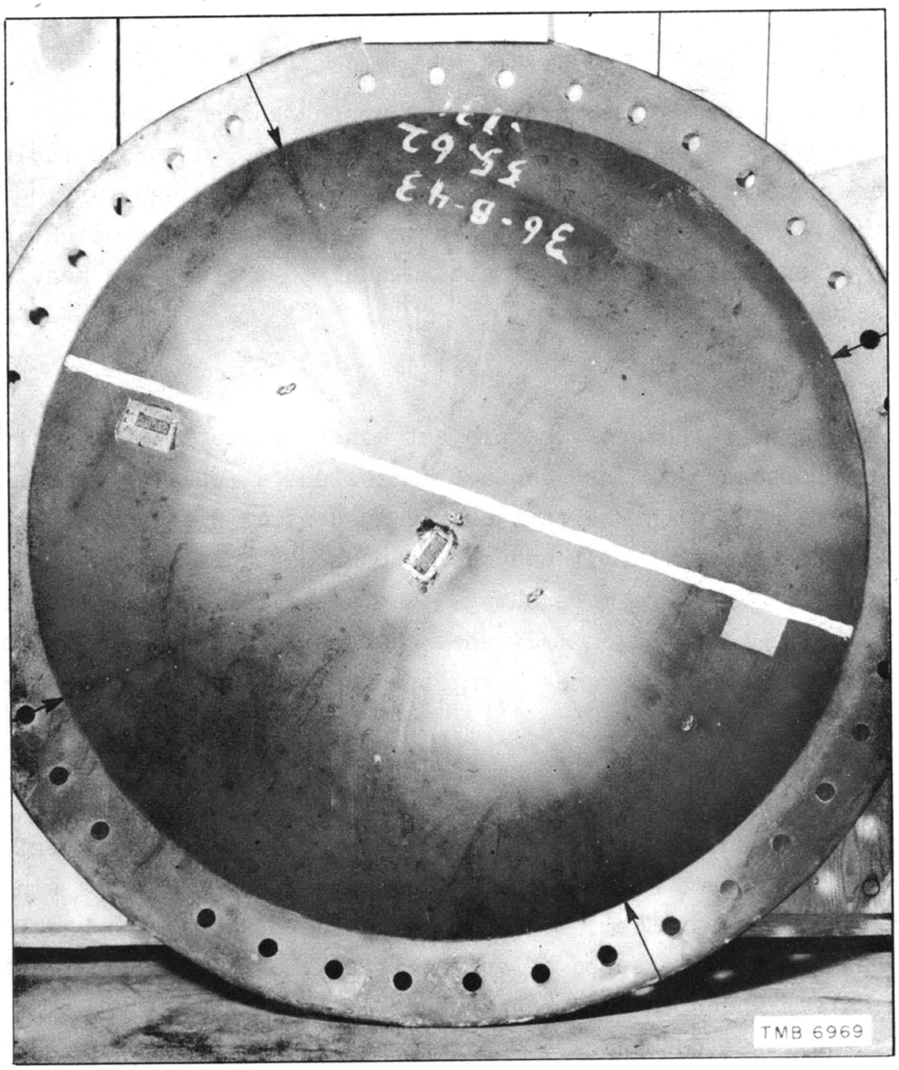


Figure 12 - Backing Diaphragm of Composite Structure, Test BW, after 3 Contact Explosions against the Facing Diaphragm

This shows the outside or underside of the diaphragm, with two metalectric strain gages still in place. The shape of the diaphragm was measured across the two diameters indicated by the arrows. Note the radial regions of concentrated strain.

Figures 13 to 20 on pages 20 to 27 show typical damage to diaphragms and composite structures of various types, as explained in the legends. Figures 15 and 18 are reproduced here as examples of the damage to filling materials of the composite assemblies.

The tests may be divided conveniently into two classes, in each of which there are six groups or configurations. The two classes comprise those with the single-plate reference diaphragms and those with the composite protective assemblies. The six groups or configurations may be listed and identified as follows:

Figure 15 - Typical Effect on Energy-Dissipative Material in a Composite Structure

The structure of this assembly is shown schematically in Table 9, page 53, opposite Test BM. Two charges of 1/2 ounce of tetryl were fired in succession in contact with the facing diaphragm. The facing diaphragm was 1/32 inch thick, and, with the charge, was placed on the near side of the 1-inch layer of roofing asphalt shown here. The rim of the 1/8-inch backing diaphragm appears around the asphalt.

The merit factor of this assembly was about 0.6.

Configuration A - Shot 1 - 1 ounce of TNT fired at 12 inches above the flat diaphragm

Configuration B - Shot 2 - 1 ounce of TNT fired at 12 inches above the deformed diaphragm

Configuration C - Shot 1 - 1 ounce of tetryl fired 12 inches above the flat diaphragm

Configuration D - Shot 2 - 1 ounce of tetryl fired 12 inches above the deformed diaphragm

Configuration E - Shot 1 - 1/2 ounce of tetryl fired in contact with the flat diaphragm

Configuration F - Shot 2 - 1/2 ounce of tetryl fired in contact with the deformed diaphragm

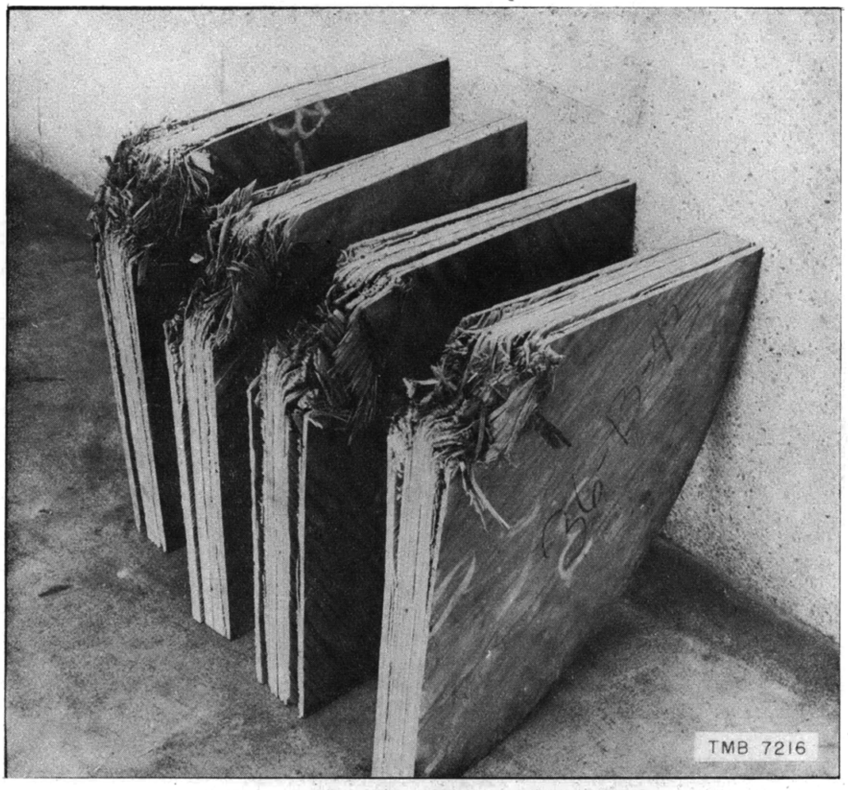


Figure 18 - Sections of 2-Inch Plywood Filling after Test BW

This is the plywood filler shown in Figures 16 and 17, sawed in four pieces to show the internal damage. Each of the 3 charges fired was 1/2 ounce of tetryl, fired against a 1/32-inch facing diaphragm on the far side of the filler.

Tables 1, 2, and 3, on pages 29, 30, and 31 of the text, present the data on single-plate steel diaphragms of various thicknesses, tested as reference or control diaphragms.

Tables 4, 5, and 6, on pages 33 to 37 inclusive, show the results for the second class of composite assemblies, subdivided according to the weight, kind, and position of the charge, and made up in the same general fashion as for Tables 1, 2, and 3. Each pair or set of entries in the table, for each type and detail of composite construction, is supplemented by a diagram showing the arrangement of the assembly and the various elements composing it. Table 4 is reproduced here as an example.

The various assemblies are listed in the order in which they were tested, with the results of both shots together. Miscellaneous data are listed in Table 7 on pages 38 to 42 inclusive.

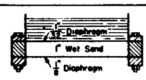
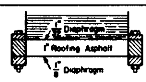
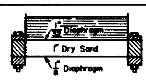
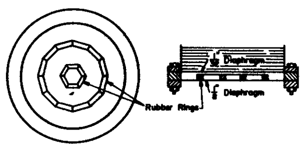
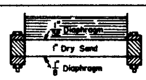
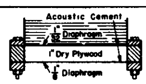
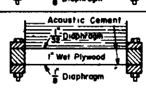
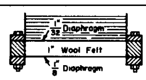
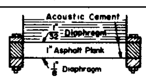
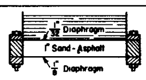
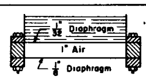
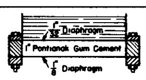
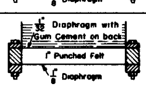
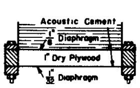
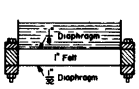
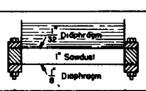
GENERAL COMMENTS ON TEST RESULTS

The outstanding results of these tests, without an analysis of any kind, may be set down briefly as follows:

TABLE 4

Test Data on Composite Protective Assemblies

A charge of 1 ounce of TNT was exploded on the axis 12 inches distant, Configurations A and B.

Test	Schematic Assembly Diagram**	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_e of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
H-1		0.1073	0.379	2.33	17.2	60600
H-2		0.1073	0.379	0.53	12.9	60600
N-1		0.0911	0.322	2.17	14.4	56100
N-2		0.0911	0.322	0.63	11.8	56100
O-1		0.1152	0.407	2.37	15.8	56100
O-2		0.1152	0.407	0.55	11.9	56100
P-1		0.0446	0.158	2.19	13.7	56100
P-2		0.0446	0.158	0.58	8.0	56100
Q-1		0.1161	0.410	2.26	15.3	56100
Q-2		0.1161	0.410	0.51	12.7	56100
R-1		0.0667	0.236	2.00	12.0	65800
R-2		0.0667	0.236	0.76	12.3	65800
S-1		0.0689	0.243	2.11	13.4	56100
S-2		0.0689	0.243	0.85	13.7	56100
T-1		0.0470	0.166	2.15	14.0	48000
T-2		0.0470	0.166	0.73	12.7	48000
V-1		0.0993	0.351	2.08	14.5	49000
V-2		0.0993	0.351	0.76	12.6	49000
Y-1		0.1183	0.418	2.41	16.9	51000*
Y-2		0.1183	0.418	0.48	14.7	51000*
Z-1		0.0418	0.148	2.26	16.2	51000*
Z-2		0.0418	0.148	0.74	11.5	51000*
BA-1		0.0876	0.310	2.67	22.2	51000*
BA-2		0.0876	0.310	0.85	21.5	51000*
BB-1		0.0583	0.206	2.36	20.7	51000*
BB-2		0.0583	0.206	1.07	18.0	51000*
BC-1		0.0743	0.263	2.15	15.0	46100
Thin Backing Diaphragm		0.0743	0.263	2.23	14.55	23100
BD-1		0.0589	0.208	2.76	20.1	45900
Thin Backing Diaphragm		No data	No data	No data	No data	No data
BG-1		0.0476	0.168	2.05	11.9	45900
BG-2		0.0476	0.168	0.50	12.0	45900

* σ_y was not measured for these cases; the average value for the control diaphragms, 51,000 pounds per square inch, was used because the control diaphragms came from the same lots of steel as the backing diaphragms.

** These and the similar diagrams in all following tables are not drawn to scale. The diaphragm thicknesses shown are only the nominal values, but the equivalent thicknesses, h_e, were derived from accurate weights by using 0.283 pound per square inch as the density of steel.

Except for assemblies containing wood, made up so as to clamp the wood at the edges, no composite structures were as effective as single steel plates of the equivalent weight per unit area. However, multiple-diaphragm constructions with air spaces proved effective; see Table 16 on page xvii.

The composite assemblies containing sand were noticeably less effective than single steel plates of equivalent weight.

For the reference diaphragms made up of single plates, the maximum center deflections on the first shots varied from about 5 1/4 inches for plates 1/16 inch thick to about 1 3/4 inch for plates 3/8 inch thick. The corresponding increases in area varied from 81 to 9.6 square inches, representing percentage increases in area* from 7.9 to 0.95, for the 1/16-inch and the 3/8-inch plates respectively.

For the composite assemblies, the maximum center deflections of the backing diaphragms, which in most cases were of 1/8-inch plate, varied from 9/16 inch to 3 7/8 inches on the first shots, for equivalent single steel plate thicknesses of 0.368 and 0.217 inch respectively. The corresponding increases in area of the backing diaphragms were 4.7 and 41.7 square inches; expressed in percentages, these were 0.46 and 4.0.

For successive shots, the increases in area of the diaphragms were of the same order, although there was a great deal of irregular variation, up to about 50 per cent. In a few cases the variation reached 200 per cent. In general, the increase in area on the first shot was larger than on any later shot.

The observed peak explosion pressures in the water at a distance of 16 inches from the charge varied from a maximum of 2840 pounds per square inch for 24.0 grams of TNT to 3610 pounds per square inch for 26.5 grams of tetryl. A peak pressure of 2130 pounds per square inch was recorded for 13.25 grams of tetryl.

A large and partly unexpected variation was found in the yield strengths of the various plates from which the reference and backing diaphragms were cut. This is, perhaps, no more than a natural consequence of the unavoidable use of whatever steel was available, over a long period of defense and war activity when steel was a critical material. Some plates showed a yield strength as low as 24,200 pounds per square inch, while others had a value as high as 65,800 pounds per square inch. The latter were of a type of high tensile steel, which was used when no medium steel was immediately available.

---

* The area of a diaphragm 36 inches in diameter is 1017.9 square inches.

METHODS OF ANALYZING DAMAGE

The simplest and most direct method of determining damage to a structure designed to resist underwater explosion is, of course, to observe whether or not it ruptures. In many previous tests this has been the only criterion used.

The next simplest method is to determine the amount of deflection that takes place in certain important members, such as the holding bulkhead. If this deflected too far, even though it held, it might derange the boilers or machinery of a ship.

The next method is to measure the increase in area of the metal in various parts of the deformed structure, as a measure of the probability of rupture. As the increase in area becomes larger, the structure may be assumed closer to rupture.

The fourth, and the most refined method known at present, is to determine and utilize the amount of energy absorbed by the structure. Assuming a given quantity of energy in the field of an explosion, and a given quantity delivered to the face of a protective structure, the structure that can absorb or reflect the largest amount of energy, or both, and pass the smallest amount along to the backing bulkhead, is considered to have the greatest merit, all other things being equal.

For the problem in hand, an excellent criterion of the usefulness of a composite structure can be obtained by converting the total weight of the protective assembly to an equivalent single thickness of steel. If the deflection or the increase in area of the backing diaphragm of the composite structure is less than the deflection or the increase in area of the equivalent thickness of steel, the composite structure is considered to have merit.

Likewise, if the energy absorbed in producing deformation in the backing diaphragm alone of a composite assembly is less than that absorbed by a single steel diaphragm of equivalent thickness, the composite structure is considered to have merit.

These energies have been calculated by two somewhat different methods in the present report, called the averaging and the individual method; the exact procedure involved in each is described in full in the report.

The merit factors derived by all four methods have been set down in a series of tables in which the behavior of different types of composite assemblies are compared. In each case a merit factor greater than 1.0 indicates that a composite structure is superior to its equivalent weight of steel in a single plate.

RESULTS OF ANALYSIS

PERFORMANCE OF FILLING MATERIALS FOR DISSIPATING EXPLOSIVE ENERGY

As a result of their investigations at the Bell Telephone Laboratories, Bond and Mason concluded that the sharp rise in pressure due to an explosion under water could be highly attenuated by interposing one or more layers of dry sand between the facing and the backing bulkheads of a protective structure.

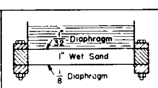
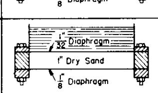
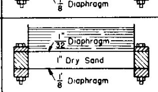
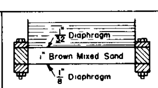
Comparison of the deflections, the increases of area, and the energy values absorbed by the 1/8-inch diaphragms in these tests shows that the sand screening does reduce all these values but that this assembly cannot compare in efficiency with a single plate of steel of equivalent weight.

The results of four tests made with sand fillings are shown in Table 8. In this and in the tables following it will be noted that the four merit factors for each test and shot differ rather widely but that they indicate clearly whether or not the composite construction is better than an equivalent weight of steel.

Although some tests performed by Bond and Mason with small 2-gram pellets of lead azide showed that the detonation wave was considerably reduced in passing through sand, and indicated that the transmission of energy

TABLE 8

Behavior of Attenuating Materials (Sand) in Protective Structures

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
1-Ounce Charge of TNT at 12 Inches, Configurations A and B											
H-1		1 inch† of wet sand	0.379	1.54	7.0	625	3680	0.66	0.41	0.24	0.17
H-2			0.379		3.6	1225	2770	**	0.28	0.23	0.44
O-1		1 inch of dry sand	0.407	1.51	6.4	450	3110	0.64	0.41	0.25	0.14
O-2			0.407		3.1	1160	2420		0.26	0.24	0.48
Q-1		1 inch of dry sand	0.410	1.51	6.4	440	3040	0.67	0.41	0.26	0.14
Q-2			0.410		3.0	1150	2580		0.24	0.22	0.45
1/2-Ounce Charge of Tetryl in Contact, Configurations E and F											
BO-1		1 inch of dry brown sand	0.439	1.53	5.1	280	1430	0.89	0.47	0.38	0.20
BO-2			0.439		4.6	600	1250		0.49	0.41	0.48

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick; in all cases the equivalent thickness was computed from accurate weights of the structures. A screened sand, -20 +30 mesh, was used in Tests H and O. In Test Q a 50-50 mixture of this fine screened sand with a commercial grade of "coarse" sand was used. Since there was no apparent difference, common brown sand, unscreened, was used in Test BO.

** Merit factors based on increase in deflection were not calculated for any second shots.

† All the dimensions given in this column in this and similar following tables are only nominal; see the second footnote to Table 4.

from the facing diaphragm to the backing diaphragm is reduced by the presence of sand, it is entirely possible that the explosion wave from the TNT and the tetryl charges used in these tests was of longer duration than was anticipated by the original theory in References (1), (2), and (3), and of longer duration than the wave produced by the lead-azide pellets. If this were the case, the attenuation produced by the sand might be considerably less. The pressure wave from the lead-azide pellets also had a steeper front than that from the TNT and the tetryl charges, indicating the presence of more energy in the form of very brief transients. These brief transients are more readily absorbed by attenuating materials such as sand than are the pulses of long duration.

Following the rather discouraging tests with sand filling, a number of other materials were tested, in which it was hoped to absorb the explosive energy by the use of dissipative and elastic materials, by adding inertia in the composite structure, or by utilizing a fluid friction principle in which water was inserted between layers of steel and then forced through small holes from one layer to the other. The materials used, the construction of the assemblies, and the results obtained are described on pages 52 to 60 inclusive. From Tables 9, 10, 11, and 12 it will be noted that very few of these structures showed merit factors exceeding 1.0.

PERFORMANCE OF COMPOSITE STRUCTURES WITH WOOD

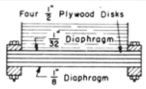
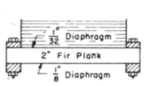
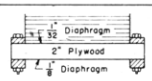
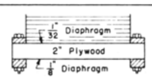
As it has long been known (8) that wood possesses considerable powers of resistance against underwater explosion, a rather extensive series of composite wood and steel structures was tested. In the first group the wood was utilized only as a filler; Table 13 on page 67 shows that this construction possessed no great merit unless the wood was very thick.

In the second group of tests with wood assemblies, the wood acted as a structural layer; the flexural stiffness of the wood was utilized by clamping the edges of the material by the same clamping ring used for the steel diaphragms. Several tests in which the wood was so arranged are reported in Table 14, reproduced here, and Table 15 on page 71, and a photograph of one of the wood layers is shown in Figure 31.

The merit factors for these latter assemblies were generally greater than 1.0. This may be ascribed, as explained in full on page 72 of the report, to the relatively greater rigidity of the wood for small deflections and to the great amount of internal friction in the wood and the shredding of the fibers which apparently takes place even after the wood has failed.

TABLE 14

Behavior of Composite Assemblies with Wood Disks Clamped at Edges

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
1/2-Ounce Charge of Tetryl in Contact, Configurations E and F											
CM-1		four 1/2-inch plywood disks, not glued	0.307	1.72	7.3	1050	516	1.55	2.29	1.94	2.03
CM-2			0.307		6.5	1050	1410		0.76	0.68	0.74
CO-1		2-inch fir plank, tongued and grooved, glued	0.251	1.86	9.0	1520	576	1.62	2.80	2.37	2.64
CO-2			0.251		8.0	1370	1670		0.86	0.78	0.82
CP-1		2-inch plywood disk	0.306	1.73	7.3	1050	370	1.94	3.50	2.75	2.84
CP-2			0.306		6.6	1060	1270		0.91	0.76	0.83
1-Ounce Charge of Tetryl at 12 Inches, Configuration C											
DD-1		2-inch plywood disk	0.299	2.00	12.8	1840	1820	1.22	1.17	0.96	1.01

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick.

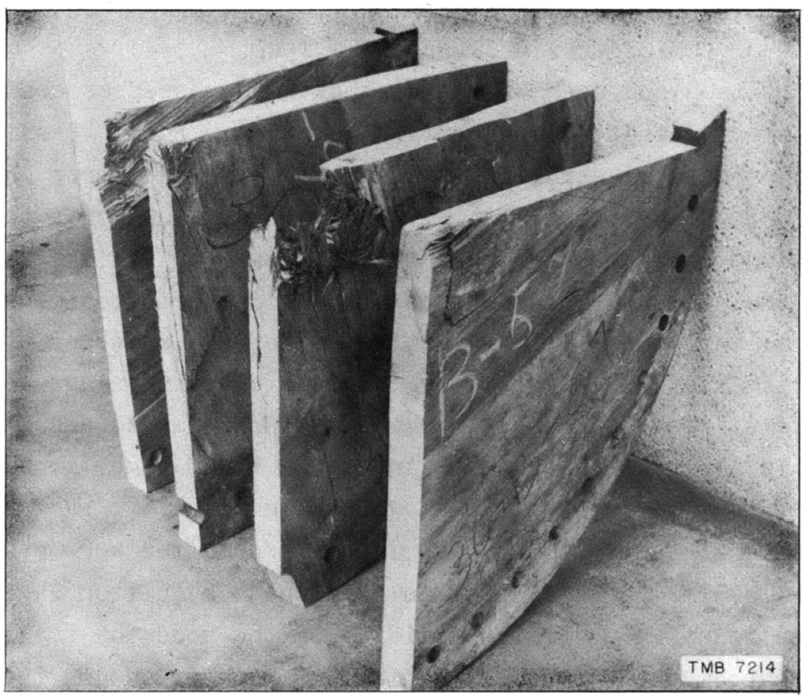


Figure 31 - Wood Structural Layer after Explosion

The structure of this assembly is shown schematically in Table 14 opposite Test CO. The wood was 2 inches thick, faced with a 1/32-inch steel diaphragm, backed with a 1/8-inch diaphragm, and attacked by two 1/2-ounce charges of tetryl fired in succession in contact with the facing diaphragm.

The merit factor of this construction was about 2.5.

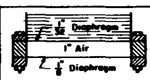
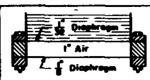
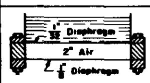
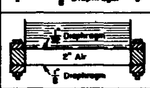
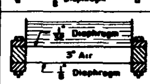
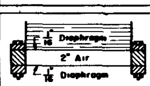
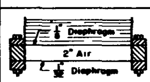
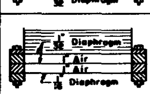
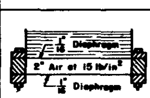
MULTIPLE-DIAPHRAGM CONSTRUCTIONS WITH AIR SPACES

A set of composite structures was also made up in which the material was divided between two or three diaphragms separated by air spaces. In substance this is the system in actual use on ships, as shown in Figures 1 and 2 of the report, and its test on a small scale was intended to serve as a check on the small-scale work, since the only large-scale data available were for systems built on this principle.

Nine different types of assemblies were built, five of which had practically the same thicknesses of facing bulkheads and backing bulkheads, but the air spaces varied in thickness from 1 inch to 3 inches. The structural details are shown schematically in Table 16.

TABLE 16

Behavior of Multiple-Diaphragm Constructions with Air Spaces

Test	Composite Structure				Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on			
	Diagram	Thickness of Layers								Increase in Deflection	Increase in Area	Energy	
		Facing Diaphragm inches	Air Space inches	Backing Diaphragm inches								Averaging Analysis	Individu Analysi
	1-Ounce Charge of TNT at 12 Inches, Configurations A and B												
Z-1		0.027	1	0.121	0.148	2.31	21.2	3750	2720*	1.02	1.31	1.12	1.38
Z-2		0.027	1	0.121	0.148		15.6	2800	2070*		1.35	1.10	1.35
	1-Ounce Charge of Tetryl at 12 Inches, Configurations C and D												
DG-1		0.031	1	0.132	0.163	2.70	25.8	4300	2530	0.90	1.16	1.51	1.70
CJ-1		0.027	2	0.122	0.149	2.83	28.5	4740	2670	1.05	1.89	1.64	1.78
CC-1		0.028	2	0.122	0.150	2.82	28.3	4700	2370	1.14	2.11	1.77	1.98
CC-2		0.028	2	0.122	0.150		23.6	4150	6570		0.68	0.58	0.63
DF-1		0.031	3	0.126	0.157	2.76	26.9	4500	1640	1.33	2.30	2.40	2.74
CQ-1		0.062	2	0.062	0.124	3.17	34.7	5650	993	1.33	3.04	**	5.69
DE-1†		0.125	2	0.030	0.155	2.78 2.78	27.3 27.3	4550 4550	600 4950	1.53 0.78	4.02 0.81	**	7.58 0.92
DZ-1		0.031	1 0.031 diaph. 1	0.062	0.124	3.17	34.8	5650	1320	1.20	2.35	**	4.28
EI-1		0.061	2††	0.062	0.123	3.18	35.1	5660	894	2.24	2.88	**	6.33

* These values are based on an assumed average yield stress of 51,000 pounds per square inch; see the first footnote to Table 4.

** Averaging analyses are not applicable to diaphragms less than 1/8 inch thick.

† Where double values are shown in this row, the upper one is based on the thin backing diaphragm and the lower one is based on the inner 1/8-inch diaphragm.

†† The pressure of the air in this space was 15 pounds per square inch above atmospheric pressure.

Of the other four assemblies, three had only one facing and one backing bulkhead and one air space each; the fourth assembly, for Test DZ, had a facing, an intermediate, and a backing bulkhead, with two air spaces.

Test EI employed a construction the same as that for Test CQ, except that in Test EI the air space in the assembly was pumped up with air to a gage pressure of 15 pounds per square inch.

It will be noted from Table 16, where the data for these tests are set down, that the merit factor improves with an increase in thickness of the air space. At first thought, it might be supposed that this is the result of reducing the effective stiffness of the facing diaphragm and hence the "swing time,"* and that consequently it constitutes a demonstration of the principles of mechanical filter theory. However, a further examination shows that the smaller deflections of the backing diaphragm are almost completely compensated for by larger deflections in the facing diaphragms. In other words, the principal merit of the larger air space lay in the fact that it permitted the facing diaphragm to deflect farther before the backing diaphragm was affected.

Test DZ, which used three diaphragms and two 1-inch air spaces, as shown in Figure 33, shows a higher merit factor than the constructions which included only one pair of diaphragms and a single 2-inch air space. However, reference to the last column of Table 17, on page 77, indicates that the 3-diaphragm construction apparently accepted and absorbed more total energy than the 2-diaphragm constructions. The result is therefore inconclusive in determining whether there was acoustic filter action.

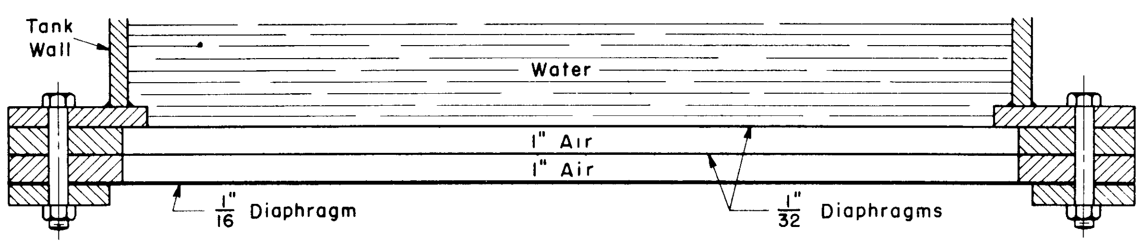


Figure 33 - Schematic Diagram of Composite Assembly for Test DZ

MULTIPLE-DIAPHRAGM CONSTRUCTIONS WITH AIR AND LIQUID FILLING

To carry still further the comparison with the protective structures actually used on ships, two assemblies were made up, CG and CH in Table 18, in which there were three layers of steel but the intervening space next to

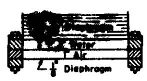
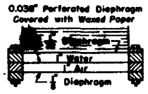
---

* This is defined as the time taken for a flexing structure to reach its value of maximum plastic deflection, reckoned from the start of the motion; see Reference (13) and Appendix 4.

TABLE 18

Behavior of Multiple-Diaphragm Constructions with Water-Air Filling

A charge of 1 ounce of tetryl was exploded on the axis 12 inches distant, Configurations C and D.

Test	Composite Structure				Equivalent Thickness h_e of Single Plate inches	Equivalent Deflection ΔZ_e inches	Equivalent Increase in Area ΔA_e square inches	Equivalent Energy in Single Plate Ω_e in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on			
	Diagram	Thickness of Diaphragms,* inches								Increase in Deflection	Increase in Area	Energy	
		Facing	Center	Backing								Averaging Analysis	Individual Analysis
CG-1		0.026	0.026	0.126	0.178** 0.306	2.55** 1.98	23.3** 12.5	3950** 1750	2320 2320	0.98** 0.76	1.69** 0.91	1.49** 0.72	1.70** 0.75
CG-2					0.178** 0.306		19.8** 10.9	3400** 1690	2340 2340		1.54** 0.84	1.38** 0.66	1.45** 0.72
CH-1	0.038" Perforated Diaphragm Covered with Waxed Paper 	0.027	0.038	0.122	0.180** 0.284	2.54** 2.04	23.0** 13.6	3850** 2000	1660 1660	1.16** 0.93	2.30** 1.36	2.02** 1.12	2.32** 1.20

* In each test there was 1 inch of water between the facing diaphragm and the center diaphragm and 1 inch of air between the center diaphragm and the backing diaphragm. In Test CH-1 the center diaphragm was perforated and covered with waxed paper.

** These values were computed by omitting the weight of water in the diaphragm structure. The water may be replaced by oil fuel on a ship. In the unstarred values the weight of the water was included, and low merit factors resulted.

the charge was filled with water, while that away from the charge was filled with air. The results are set down in Table 18.

The merit factors derived will depend on whether it is considered necessary to include the weight of the liquid as part of the protective system. However, as the liquid on a ship may be oil fuel, which has to be carried in any event, its weight may be omitted. Under this assumption, a ratio of merit of the order of 1.5 is obtained in Test CG; this ratio is even higher, about 2.0 or more, for Test CH, in which the middle diaphragm was perforated. The merit factor for Test CG is slightly less than for Test CJ* in which the middle diaphragm was omitted and no liquid was used, and considerably less than for Test DF with its 3-inch air space. It is therefore concluded that, although the division of the metal into two separate bulkheads may be of some help, it is mainly the presence of the thicker air space which accounts for the benefit. Filling part of it with liquid (water) appears to be of no benefit;** on the contrary, this would reduce the protective effect, when the weight of the liquid is considered.

COMBINATIONS OF WOOD WITH AIR SPACES

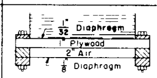
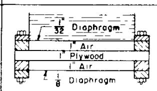
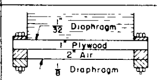
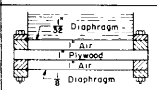
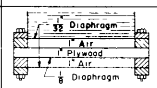
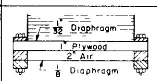
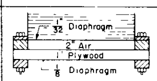
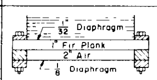
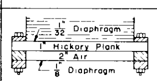
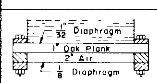
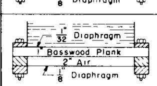
Since the two most successful means of protection developed were multiple-bulkhead constructions containing air spaces, and constructions

* See Table 16 on page xvii.

** The value of the liquid in reducing the fragmentation effect is not considered here.

TABLE 19

Behavior of Composite Assemblies of Clamped Wood with Air Spaces

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
		1/2-Ounce Charge of Tetryl in Contact, Configuration E									
CU-1		1-inch plywood disk, clamped, 2 inches of air	0.240	1.88	9.4	1640	311	1.88	5.21	4.65	5.27
DK-1		1 inch of air, 1-inch plywood disk, clamped, 1 inch of air	0.233	1.91	9.7	1720	250	1.46	4.03	5.79	6.88
DN-1		1-inch plywood disk, clamped, 2 inches of air	0.233	1.91	9.7	1720	370	1.43	3.02	4.07	4.65
		1-Ounce Charge of Tetryl at 12 Inches, Configuration C									
DI-1		1 inch of air, 1-inch plywood disk, clamped, 1 inch of air	0.231	2.23	17.4	2790	700	1.46	2.72	3.45	3.99
DL-1†		1 inch of air, 1-inch plywood disk, 1/8-inch diaphragm, 1 inch of air	0.263	2.10 2.10	14.9 14.9	2280 2280	540 1350	0.99 0.94	2.07 1.30	**	4.22 1.69
DM-1		1-inch plywood disk, clamped, 2 inches of air	0.232	2.22	17.3	2760	1130	1.19	1.82	2.16	2.44
DW-1		2 inches of air, 1-inch plywood disk	0.225	2.27	17.9	2900	1360	1.17	1.99	1.84	2.13
EE-1		1-inch fir plank, 2 inches of air	0.205	2.37	19.9	3280	1100	1.27	2.34	2.58	2.98
EF-1		1-inch hickory plank, 2 inches of air	0.237	2.20	16.9	2700	557	1.44	3.93	4.19	4.85
EG-1		1-inch oak plank, 2 inches of air	0.241	2.18	16.6	2620	830	1.34	2.59	2.75	3.16
EH-1		1-inch basswood plank, 2 inches of air	0.201	2.39	20.4	3350	732	1.45	3.58	3.95	4.58

* All backing diaphragms in this group were about 1/8 inch thick, except in Test DL in which the backing diaphragm was about 1/32 inch thick. All facing diaphragms were about 1/32 inch thick.

** Averaging analyses are not applicable to diaphragms less than 1/8 inch thick.

† Where double values are shown in this row, the upper one is based on the thin backing diaphragm and the lower one is based on the center 1/8-inch diaphragm.

containing wood, the next step was to try arrangements in which both protective devices were used. A series of diaphragm models were accordingly made up, each model consisting of three diaphragms of steel and wood combined in various relative positions. The data are set down for comparison in Table 19.

The most encouraging feature about this set of experiments, aside from the relatively high merit factors of these constructions, was the fact that the protection provided by each of the two devices apparently supplemented that of the other. The wood when used in combination with an air space was always better than the air space alone, or better than the wood alone.

MISCELLANEOUS

A number of additional experiments are reported in Tables 4, 5, and 6 which did not fall into any of the classifications hitherto listed. Among these may be mentioned two tests on concrete, BX and BY; see Table 6 on pages 36 and 37. The former had a filler made up with a standard 1-2-4 mix in which a pea-gravel aggregate was used; the filler in the latter was a similar mix with a special light-weight aggregate. Both concrete disks gave appreciable protection but not enough to justify the added weight.

Several tests were also made in an attempt to force the explosion to do more work in distorting the facing diaphragm by one device or another. Tests CW and DB are examples; see Table 5 on pages 34 and 35. These were not particularly successful.

Following the rather successful experiments with combinations of air spaces and wood, special designs for 1/16-scale box or caisson models were prepared by the use of the general scheme which had been followed by the Bureau of Ships for a number of years in tests of this kind at the Norfolk Navy Yard.

Three such models were built by the Taylor Model Basin and were tested at Norfolk but with indifferent results; see Appendix 3. It is hoped to describe this phase of the work more fully in a separate report.

Two 1/16-scale caisson models were also built at Norfolk (15) (16) to designs supplied by Bond and Mason. Details of the results of these tests are not available.

SUMMARY AND CONCLUSIONS

Despite the rather severe limitations of the test procedure and the considerable number of apparent discrepancies in the test results, it is nevertheless possible to draw certain conclusions from the data.

Attempts to apply mechanical-filter theory to the design of protective constructions in the cylindrical open test tank have for the most part been unsuccessful. The tests which appeared to offer the best application of the theory were those employing pure inertia, and the corresponding assemblies were found to be without merit.

These tests bear out previous investigations which established the merit of multiple-bulkhead systems with air spaces between. With the exception of sawdust, no filler material was found more suitable than a simple air layer.

The tests verified the fact, already known from previous small-scale and full-scale tests, that wood possesses considerable protective power against contact or non-contact explosions.

Placing the wood behind a steel facing enhances its protective value and prevents corrosion of the steel and rotting of the wood. Placing the wood in front of another steel facing supports it while the energy is being absorbed in shredding the fibers. Wood used as a protective layer should be worked in as structural members, securely held in place, rather than as filling.

Greater spacings between diaphragms appear desirable and there is a suggestion that the optimum distribution of steel among bulkheads or diaphragms warrants further study.

TABLE OF CONTENTS

MODEL TESTS OF COMPOSITE STRUCTURES TO RESIST UNDERWATER EXPLOSION

ABSTRACT

The design of the structure to protect naval vessels against underwater explosion has in the past been developed on a basis of experience with a large number of model test structures and with actual damage in service, without adequate knowledge of the basic fundamentals.

Novel theories advanced by W.P. Mason and W.L. Bond of the Bell Telephone Laboratories, relating to the time constants of the structure and of the explosion as the essential variables, led to authorization by the Bureau of Ships for a program of small-scale experiments on thin circular diaphragms at the David Taylor Model Basin.

Various composite structures were developed and tested. The tests involved the use of dissipative, attenuating, inert, and elastic filling materials between steel disks, and the use of wood, both clamped and unclamped at the rim. Various multiple-diaphragm constructions using combinations of air, water, and wood filling were also tried. A series of unprotected steel diaphragms of various thicknesses were tested to furnish control or reference data.

The data for the diaphragms are tabulated on the bases of maximum center deflection, increase in area under explosive load, and energy absorption. Merit factors are assigned for comparing the various composite structures with relation to an equivalent weight of steel, and the performance of the various materials and structures is discussed.

It is found that multiple-layer constructions, with air-and-water filling, and various combinations of wood and steel, have greater protecting power than single steel plates of equivalent weight.

INTRODUCTION

With the steadily increasing use of the automobile torpedo and the submarine mine, and with large increases in the weight of the charges carried by these weapons, warship designers have been hard pressed to devise systems of underwater protection which would be adequate to protect the vitals of a vessel from fatal flooding. Development and experience have evolved a more or less standard design of protection, about as shown in Figure 1, which is made up of a number of adjacent and parallel layers of steel with layers of air or liquid in between.

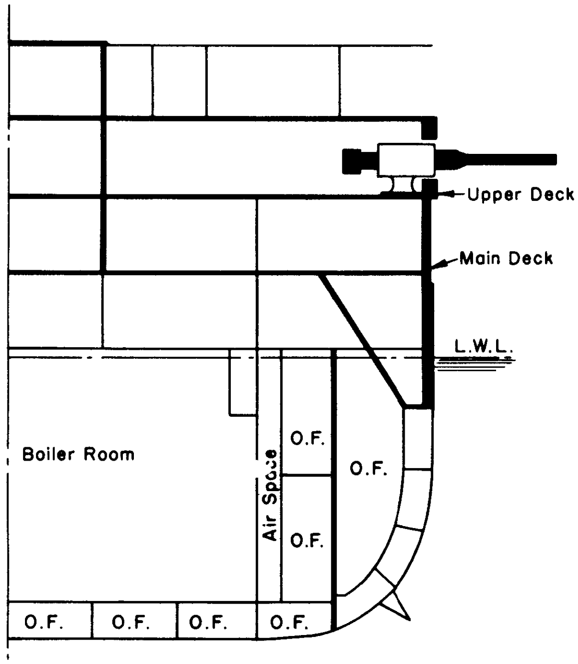


Figure 1 - Diagram Showing Typical Protection against Underwater Explosion in a Capital Ship*

This half-section does not represent the most modern ideas of protection, but it illustrates the general features, in which there are several bulkheads, one behind the other. The spaces between are filled with air, oil fuel, or even sea water, as may be found most advisable for protection and for control of list in the event of damage.

Owing to a lack of fundamental knowledge both of the behavior of the steel of the ship structure and of the forces generated by the explosion, in the extremely short period in which the phenomenon takes place, the design of the various protective structures proposed and used in the past has to a large extent been based on consideration of static loads. As time went on and actual experience with these constructions under explosive loading became available, either in special tests or in enemy action, the construction has been modified accordingly.

In the course of the extended research on protection against underwater explosion conducted by the navies of the world during the past three or four decades, a number of assemblies have been studied in which various combinations of steel, wood, coal, hollow metal tubes, and other materials were used as a cushioning device to absorb explosive energy and to protect the vitals of a ship. Combinations of steel, wood, and pipes were actually employed in some British men-of-war built in the period of the first World War.

About three and a half years ago a decidedly novel system of explosion protection for naval vessels was proposed to the Bureau of Ships. This system of protection attempted to take advantage of the *dynamical* characteristics of the underwater explosion by the use of a theory which had proved beneficial in similar fields elsewhere, particularly in acoustics. From this

* This diagram is taken from a paper entitled "Naval Construction During the War," by Sir Eustace Tennyson d'Eyncourt, Director of Naval Construction, British Admiralty, Transactions of the Institution of Naval Architects, Vol. LXI, 1919, pp. 66-93; plates VII-XXVI, inclusive.

point of view the time constants of the structure and the time constants of the explosion are conceived to be the essential variables.*

The authors of this system, W.L. Bond and W.P. Mason of the Bell Telephone Laboratories proposed (1) (2) (3)** that mechanical impedance and filter theory be applied to the design of explosion protection shields. Evidence from small-scale experiments made by them indicated that a more effective shield could be obtained by incorporating an attenuating medium such as sand in the outside layer of the protective structure than by using metal alone. In essence, the proposal contemplated a construction having a natural period of oscillation so long that the energy from the very brief explosion wave could readily be stored elastically in the structure and returned to the water later.

There is a fairly close analogy here with standard principles of vibration isolation as applied to rotating and reciprocating machinery. The mechanical filter in such a case becomes what is known as a low-pass filter, one which will reject energy in frequencies well above its own natural frequency but will pass the energy of frequencies below this value.

The addition of sand was found necessary in the inventors' experiments because of the fact that a resilient structure could not be made strong enough to store the necessary quantity of energy even when the time constants had been properly adjusted. In this sense the sand behaves as a resistance or dissipative element in series with the mechanical filter. The inventors also proposed springs between the parts of the structure, in addition to the sand, to cushion the low-frequency components of the shock.

This report presents the results of a series of small-scale experiments undertaken by the David Taylor Model Basin at the request of the Bureau of Ships (4) (5) to examine the merit of the proposal made by Bond and Mason.

Since there was some uncertainty in the application of the mechanical filter theory to the particular protective assembly proposed, a number of other composite protective structures were developed by the Taylor Model Basin and tested in an effort to achieve the same type of action. The reasons for this are discussed in subsequent sections, and the structures are shown by diagrams in Tables 4, 5, and 6 on pages 33 to 37. The fundamental idea behind all these schemes, of course, was to find some material or combination of materials capable of dissipating or reflecting more energy for a given deflection and for a given weight than shipbuilding steel.

---

* Some phases of this theory have recently been discussed in TMB Reports 481 and 507 on the effect of impact on simple elastic structures.

** Numbers in parentheses indicate references on page 85 of this report.

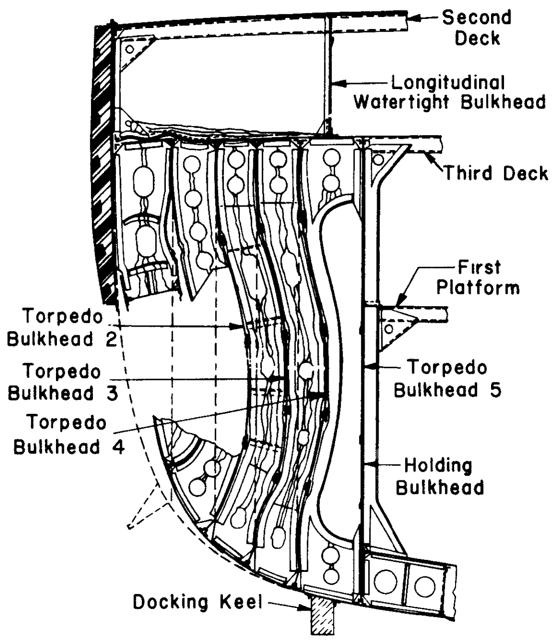


Figure 2 - Diagram Illustrating Underwater Explosion Damage to the Protective Structure of a Capital Ship

Provided the holding bulkhead remains intact, severe damage to the outer layers of the protective structure does not endanger the ship.

If most of the space between the protective layers is filled with oil or water before the damage occurs, the increase in flooding is small.

The test setup which the Taylor Model Basin used was in many respects quite different from that of Bond and Mason and was also quite different from the actual ship installation. For this reason the entire series of experiments is regarded as being purely comparative; no attempt is made throughout this report to draw conclusions from them in terms of absolute quantities.

The general procedure in the Taylor Model Basin experiments was to test a simple steel structure as a reference or control structure and then to examine the effect of various protective structures in front of, or in combination with, the steel. It is believed that the trends indicated in these experiments can probably be used in designing larger-scale model structures. Figures of merit have been developed, but they are still entirely comparative.

The manner in which the various outer bulkheads of a modern torpedo-defense structure in a capital ship protect the innermost or holding bulkhead, which in turn protects the vitals of the ship, is shown graphically in Figure 2.

GENERAL CONSIDERATIONS

Before proceeding to a description of the test apparatus and procedure, it is desired to include a statement at this point covering certain general features of explosion phenomena, notwithstanding that some of the points brought out here did not appear in this definite form when the project was started nearly four years ago.

The explosive energy which reaches a protective structure from the water undergoes three types of transformation. Some of the energy is dissipated in the form of heat or mechanical work on the protective structure, some is reflected back into the water, and some is transmitted to other parts of the larger ship structure. If actual rupture occurs in the material of the protective assembly, this is considered a type of mechanical work.

In the design of protective layers or elements for a ship structure, one of the aims is to prevent any appreciable part of the energy from reaching the inner structures surrounding the vital portions of the ship; the damage should be confined principally to the protective element, as shown in Figure 2. This means that the explosive energy must be expended in deforming or tearing apart some of the protective structure and thus be dissipated into heat, or it must be reflected back into the water.

Energy dissipation occurs when plastic work is done on a steel assembly, and presumably when a change in shape is produced in materials such as asphalt, coal, wood, and the like.

As mentioned previously on page 3, it was hoped by Mason and Bond that friction between grains of sand in one or more of the protective layers might be utilized to produce this type of energy dissipation. Although the idea of getting rid of explosive energy by a cushioning procedure was by no means new, the theory behind the protective screen proposed by them was apparently novel. In view of the high authority of the sponsorship, it deserved serious consideration. All test programs were reviewed by individuals familiar with mechanical-impedance theory.

No attempt was made to achieve similitude with a ship structure in these tests. As explained in detail in a subsequent section, the explosive charges were set off in water in an open tank, a procedure which had been used several times before this (6) (7). The assembly to be tested, called the "sandwich," formed the bottom of the tank. This assembly comprised a diaphragm simulating the innermost or holding bulkhead of a torpedo protection system, with the shield or screen to be tested interposed between the charge and the diaphragm. In most cases a facing of sheet metal was included but this was thin and definitely a part of the screen.

Since the charge was fired in a relatively small enclosure, the expansion and contraction of the gas globe* was subject to some restriction, and the results of the tests may lose some validity on this account. Furthermore, the effect of the explosion energy striking the walls of the tank must

---

* It is assumed that the reader is familiar with this phenomenon. If not, he will find the essential features covered in TMB CONFIDENTIAL Report 512, entitled "Motions of a Pulsating Gas Globe Under Water - A Photographic Study," by Lt. D.C. Campbell, USNR, May 1943.

be considered. Some of this energy was undoubtedly reflected by the tank walls toward the diaphragm at the bottom, with the result that more energy reached the diaphragm than would otherwise have been the case. The time duration of the force was also greater than in open water. These considerations emphasize the reasons for devoting attention only to the comparative nature of the test results.

The limitations described here and elsewhere were recognized at the outset of the work, and they were accepted at that time (1940) because there was no alternative to get the test program underway.

The thin circular diaphragm adopted for these early tests and described in the section following lent itself remarkably well to use as a sort of damage gage. It was not only easily fabricated and assembled, but its deformation could easily be measured after the explosion, and the amount of energy absorbed by it could be estimated by a consideration of the increase in area of the diaphragm inside the supports* and by a knowledge of its thickness and the yield strength of the material.

More than 120 protective assemblies were tested. Although various methods of measurement were used interest, in general, centered on the deformation and the residual increase in area of the diaphragm caused by the explosion, and on the weight of the whole assembly. The screening effect was considered to be indicated by the energy prevented by the screen from reaching and deforming the backing diaphragm. The manner of accomplishing this is explained subsequently in the report.

It should be borne in mind throughout the description of these tests and the consideration and discussion of the results that the first of the tests described here were among the first of the items on the now greatly expanded underwater-research program of the Taylor Model Basin. This early series of tests was somewhat hampered by a lack of refined measuring equipment and by shortages in critical materials. For developments and refinements growing out of this early work reference should be made to later work at the Taylor Model Basin on which reports have already been issued.

PROTECTIVE ASSEMBLIES OF VARIOUS MATERIALS

Not long after the proposal for the use of sand in protective structures was made, an oral account was given to the Taylor Model Basin by Professor George B. Karelitz of Columbia University, describing experiments

---

* If the diaphragm assumes a spherical shape after the explosion, the increase in area $\Delta A = \pi(\Delta Z)^2$, where ΔZ is the increase in center deflection due to the explosion; see Appendix 4. However, this formula was not used in calculating ΔA for these tests because the final shape was not exactly spherical.

conducted by the Russian Admiralty prior to 1917 on the protective effect of wood. With Professor Karelitz' assistance, a written statement in some detail (8), prepared by the man who proposed and conducted the Russian tests, Mr. N. Artsay, was later obtained.

Mr. Artsay, who is now employed in the United States by the Foster-Wheeler Corporation, was at the time of the First World War, when the test in question was being made, a naval architect with the rank of Lieutenant in the Imperial Russian Navy.

More recently the scheme of Artsay has formed the substance of a report entitled "Study of Seagoing Tug for Special Duty," by V.S. Makaroff, dated September 1942 (8).

This report contains a considerable amount of interesting historical data and gives brief accounts of various tests conducted by the Russian Navy on both model and full-scale structures. It should be read by anyone who is interested in familiarizing himself with the use of wood as protection against underwater explosions.

The Russian reports made such a favorable impression when they were studied that the Taylor Model Basin program for the test of composite structures embodying sand was expanded to include the use of wood. For reasons given in subsequent sections in which the test data are analyzed, the program was extended to cover the use of many other materials which, either by their inherent character and composition, or by the nature of their use in the structure, were thought to have properties which would make them valuable in an underwater-explosion-protective system.

TEST ARRANGEMENT

Instead of making up a small box or model caisson in which the protective arrangement was incorporated in one face, and firing a charge at or near this face in relatively free water, as had been the practice in the U.S. Navy for many years previously, the Taylor Model Basin fitted the protective assembly to be tested as the circular bottom in a vertical cylindrical tank and then filled the tank with water, as shown in Figure 3. Both structural elements were in the form of thin circular membranes or diaphragms, clamped rather firmly at the edges.

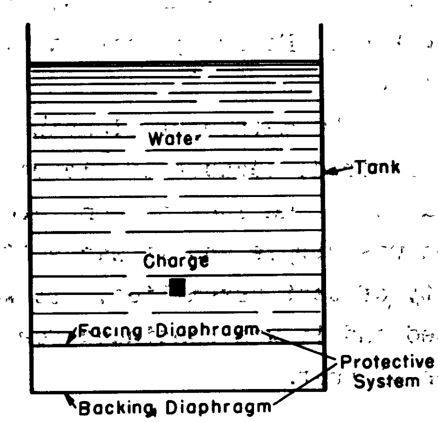


Figure 3 - Schematic Arrangement for Model Tests

For some of the tests the charge was in contact with the center of the facing diaphragm.

If, in an assembly of this kind, the charge weights and positions are limited to those which will not produce rupture, the diaphragms will deform downward into roughly spherical shape. As such they will form model structural members in which the deformation, the elastic and plastic stress, and other features are amenable to theoretical treatment (7).

In this arrangement, the upper or facing diaphragm is intended to represent a panel in the outer shell in the side of a ship, facing a bomb, torpedo, or mine explosion. The lower or backing diaphragm, as illustrated in the diagram of Figure 3, is considered to represent the holding bulkhead in the ship, which forms the outer boundary of the vital machinery and magazine spaces. The remainder of the protective system lies between the two diaphragms in each case.

The purpose of each test was to determine the amount of deformation and the energy absorbed and retained by the diaphragm - generally the backing diaphragm - in consequence of the explosion.

TEST APPARATUS

GENERAL

Figure 4 shows the arrangement of the test tank used to hold the diaphragms in these experiments, together with the charge and the gages. It includes also a detail diagram of one of the composite test assemblies, and an indication of the method by which these assemblies were held in the bottom of the tank. Figure 5 shows a diaphragm bolted in place in the bottom of the test tank.

The method of clamping the test diaphragms at the edges left much to be desired, because of clearance in the bolt holes, permissible motion at the gaskets, and lack of complete rigidity at the boundaries. However, the method was simple and it was sufficiently flexible to accommodate a great variety of test assemblies. It was adopted when nothing better had been developed and it was continued for the sake of consistency throughout the series of tests.

EXPLOSIVE CHARGES

Two types of explosive were used, TNT and tetryl, in 1/2-ounce and 1-ounce charges.* In the tests up to and including that of Model BG-2,** TNT

---

* The "1/2-ounce" and "1-ounce" designations are nominal. The 1/2-ounce charges were 13 1/4 grams; the 1-ounce charges varied from 23.1 to 28.8 grams. Since the variation in damage with charge size is a function which has not been definitely established for this tank, no corrections are made in this report for actual as compared with nominal charge size. Table 7 gives the actual charge weights used.

** See Table 4 on page 33.

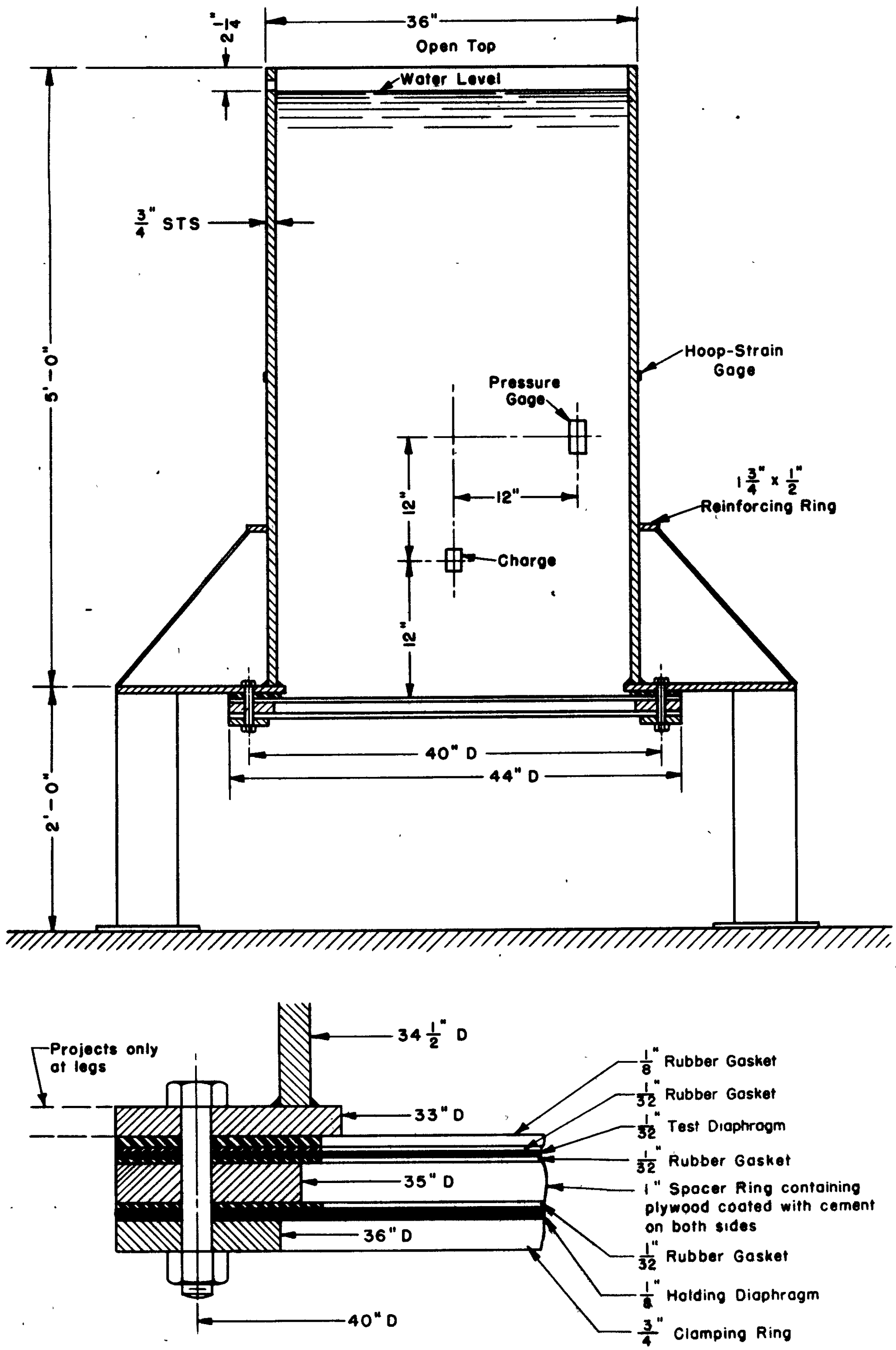


Figure 4 - Tripod Tank and Typical Test Assembly

The upper diagram is drawn to scale, and the positions of the charge and the gages apply to non-contact shots. The details of the typical protective assembly are for Test BL which was tested with 2 contact charges.

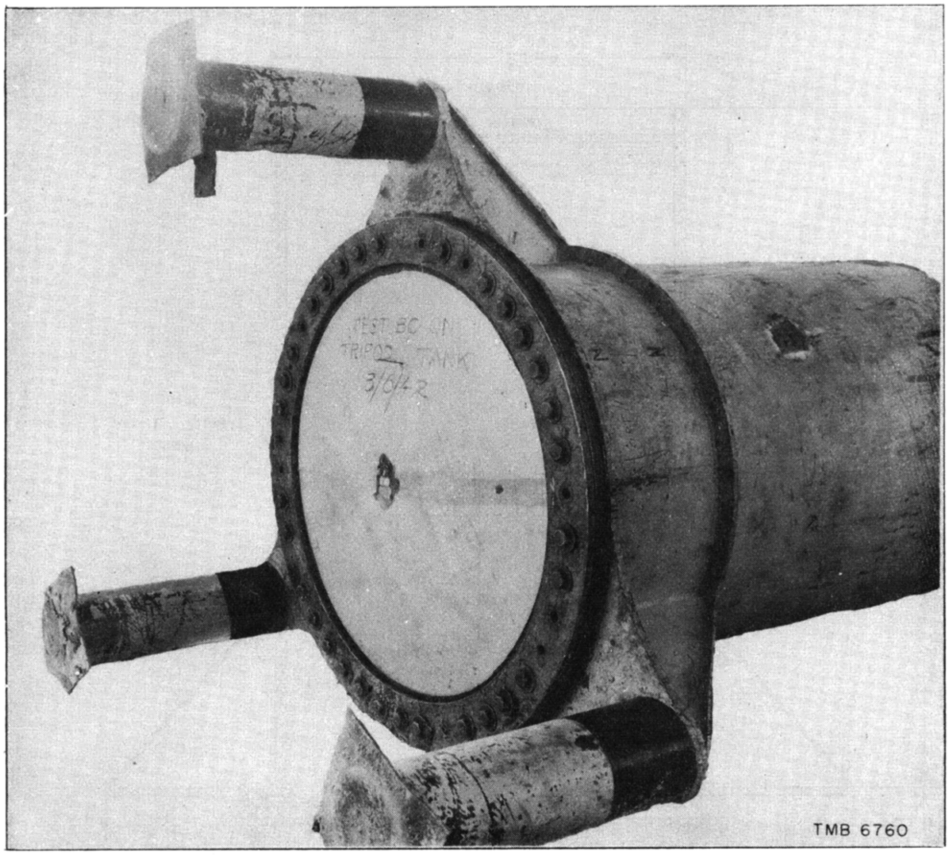


Figure 5 - General View of Bottom of Tripod Tank with Test Assembly in Place

As shown in this and in subsequent photographs, the diaphragms were held in place by 39 bolts, each 3/4 inch in diameter. These retaining bolts were placed in sets of 13, equally spaced between the centerlines of successive legs, with no bolt holes in the tank flange or diaphragm at the tank legs. This photograph shows some extra holes which were made in the bottom retaining ring to mount lifting eyes and other equipment. Eight of the 39 retaining bolts have been removed here, preparatory to disassembly.

charges were used exclusively. Subsequent to this test tetryl charges were used in all cases except for Models BI-1, BI-2, and BJ-1. Tetryl has been found to be a more reliable explosive than TNT for use in small charges; comparison of the curves in Figure 6 shows that in a charge of this size the tetryl produces about 35 per cent more damage than TNT, as measured by the increase in area of a simple steel diaphragm. This matter is treated at somewhat greater length in Appendix 2.

For purposes of similitude tetryl represents full-scale charges of TNT more accurately than would small charges of TNT itself, since the full speed of detonation is not attained in TNT until a considerable extent of the explosive material has been traversed.

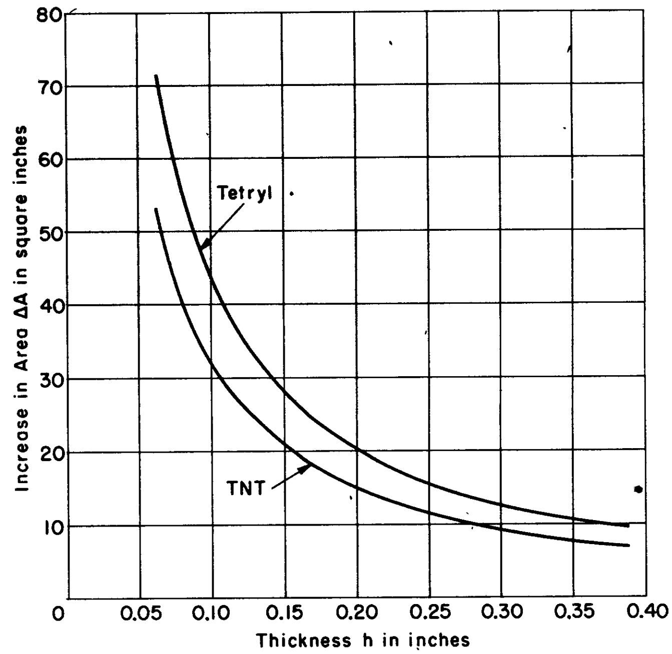


Figure 6 - Increase in Area in Simple Diaphragms Caused by Different Explosives

The data from which these curves were drawn were derived from tests on single-plate steel diaphragms of 36 inches free diameter, loaded by explosion in the tripod tank of 1-ounce charges at 12 inches distance.

The data for the upper curve were taken from tests on Configuration C, those on the lower curve from Configuration A; see page 28.

INSTRUMENTS AND RECORDS

During each explosion two and sometimes three records were made, all as a function of time:

a. Pressure in the water.

In the early series use was made of a rubber-coated resistance-sensitive gage in which the resistance of the active element was altered by the change in pressure in the water. Later this was replaced by a piezoelectric gage consisting of an insulated tourmaline crystal which generated a quantity of electricity proportional to the applied pressure.

b. Hoop strain on the wall of the tank.

One or more metalectric strain gages were attached to the outside surface of the tank.

c. Strain in the lower or backing diaphragm.

This was obtained by a metalectric strain gage placed on the lower or dry side, but it could not be done consistently as the technique was not adequate at very high strain values.

All the records for a, b, and c were made on film by cathode-ray oscillographs. Two such records are shown in Figure 7.

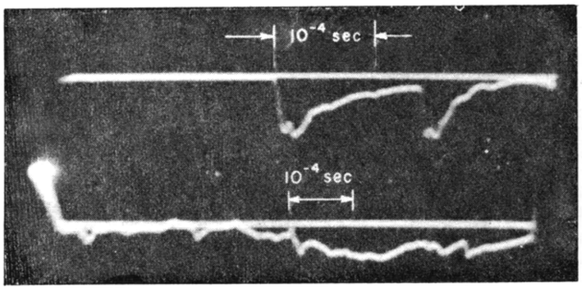


Figure 7a - Oscillogram from Pressure Gage

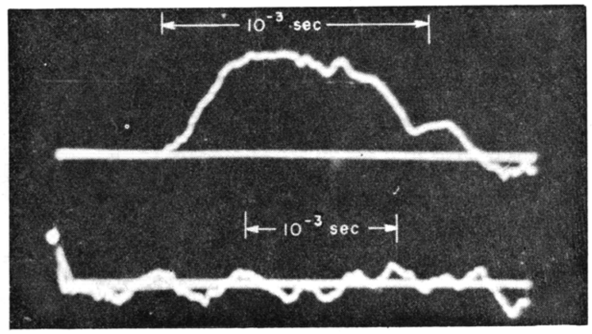


Figure 7b - Oscillogram from Hoop-Strain Gage

Figure 7 - Typical Oscillograms from the Pressure Gage and the Hoop-Strain Gages

These records were made during the test of Assembly R-1. In Figure 7a, a positive pressure is recorded as downward.

In these "round-trip" sweep records, the trace moves from left to right in the upper line and from right to left in the lower line.

At the time this work was done it was not possible to apply accurate calibration factors to the vertical coordinates.

After each shot, profile measurements of the permanent residual deflection of the underside of the backing diaphragm were made by dial gages at 18 points across a diameter, or, in some cases, at 15 points across each of two diameters at right angles. In a later series continuous profiles were taken by a device with a pointer which followed the contours of the diaphragms from edge to edge. A typical record obtained by the use of this apparatus is shown in Figure 8.

Because of the many different types of steel employed in the diaphragms, at least one longitudinal and one transverse tensile specimen were taken from each sheet of steel used for making the diaphragms. A load-elongation curve was obtained for each specimen by the procedure usual in static tensile tests.

Streak records, giving a photographic record on a time base of the axial deflection of the diaphragm during the explosion, were made on a few of the diaphragms during the course of this project, in an effort to develop a satisfactory technique. The method of accomplishing this, using the more refined methods later developed, is shown in Reference (9).

TEST PROCEDURE

REFERENCE DIAPHRAGMS

To permit comparison between the performance of composite structures of various types and of simple steel diaphragms, a considerable number of tests were made with single steel diaphragms of thicknesses varying from 1/16

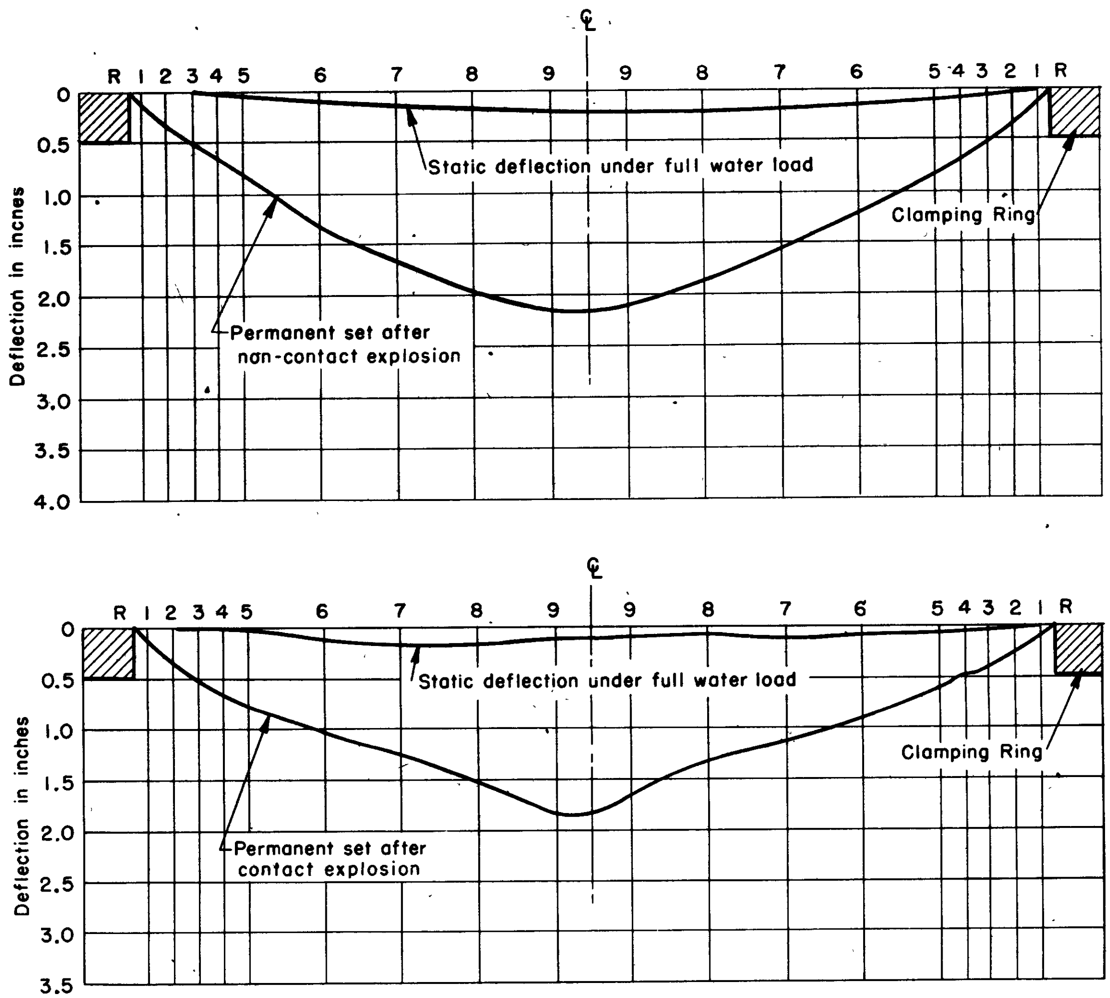


Figure 8 - Typical Deformation Contours of Backing Diaphragms, Before and After the Explosion

In each diagram, the upper line represents the deformation due to the head of water in the test tank. The deflection under explosive load was taken as the difference between the two.

The maximum deflection in every case occurred at or very close to the center of the diaphragm.

inch to 3/8 inch. The heaviest single diaphragms had a weight per square inch of exposed area approximately equal to that of the heaviest composite structures.

POSITION OF CHARGES

Since the purpose of the project was to investigate structures suitable for protection against contact explosions as well as near misses, experiments were made with the test charge in contact with the structure as well as 12 inches above it. It had been supposed that a charge in contact with the structure would do more damage than a similar charge at a distance of 12 inches. For this reason 1/2-ounce charges were used for the contact explosions instead of the 1-ounce charges which were normally used for non-contact shots. As it developed, the damage due to a contact charge in this tank differs only slightly from that due to a charge of the same size and composition at a distance of 12 inches.

MULTIPLE SHOTS

It was found in a number of preliminary tests in this series that the diaphragms had by no means reached the rupture point after a single charge had been fired against them. To take advantage of this, it was decided to fire two shots at each plate or assembly. The backing diaphragms were carefully measured after the first shot, and second shots were then fired, after which the diaphragms were again measured.

It was thus possible to obtain a second set of data on each plate or assembly with no more trouble than to reset the instruments and insert another charge in the tank. In some cases more than two charges were fired in order to increase the ultimate damage.

When the second shots were fired the charge had to be placed lower than the position shown in Figure 4 to maintain the 12-inch distance to the deflected diaphragm. The pressure gages for the second shots were lowered to correspond, but the hoop-strain gages were left in the same position.

CALIBRATION OF INSTRUMENTS AND PRECISION OF MEASUREMENT

Unfortunately, at the time most of these tests were made, the underwater-explosion pressure gages had not reached a high degree of development, so that the results from these gages leave much to be desired. However, the records served quite well as indications that the same degree of detonation was being obtained on supposedly identical shots.

The hoop-strain and the pressure records described in a previous section on page 11 were employed mainly as controls on the uniformity of the explosion. With one or two exceptions these explosions were consistent.

To check the hoop-strain measurements, an elaborate series of comparisons was made with six hoop-strain gages used simultaneously. These showed a probable error of 3.7 per cent for any one measurement of the peak elastic strains due to the explosion, and a maximum deviation of 13 per cent. These figures include variations both in the explosion and in the performance of the strain gage.

TEST RESULTS

GENERAL

Of all the test data taken, the most important for purposes of analysis were found to be the maximum deflection of the single plate and the backing diaphragms, the increase in area of these diaphragms inside the clamping rings, derived from the final shape, and the yield strength of the materials used.

A few general features affecting the reliability, accuracy, and usefulness of these results, which were not fully apparent until the tests were completed, should be noted here.

As indicated in Figures 9a and 9b, and in a number of other photographs reproduced subsequently, the contact charges were not always positioned at the exact centers of the diaphragms. This feature is probably responsible for the off-center maximum deflections noted in a number of backing diaphragms, as shown in Figure 10.

The irregular contours of the backing diaphragms under the static water load in the tank, such as appear in Figures 10 and 11, may be due to irregularities in the material of the backing diaphragms, to irregularities in the filling materials of the composite assemblies, or to difficulties in making up the composite assemblies.

Commercial rolled sheet steel, both black and galvanized, such as was used for many of the parts in these tests, is notoriously irregular in characteristics and behavior. It is known, for instance, that black-steel sheet will not roll up into a smooth and uniform cylinder of reasonably small radius. The regions of localized strain shown in Figure 12 indicate that something of the kind may be responsible for irregular behavior here.

Under the heavy radial loads encountered in these tests, the holes in the diaphragms for the clamping bolts elongated, and probably the whole clamping assembly at the rim twisted or deformed elastically at the moment of greatest load. The rubber gaskets used for watertightness were certainly responsible for a considerable degree of flexibility at the rim. These were eliminated on later projects of this kind (10) but only at considerable expense and some complication.

The charges were not all of uniform weight, but to have introduced a correction here might only have increased the uncertainty, without benefit to the validity of the final results.

Figures 13 to 20, inclusive, show typical damage to diaphragms and composite structures of various types, as explained in the legends. Other photographs of this kind are reproduced subsequently, in connection with the analysis of the results.

(Text continued on page 28)

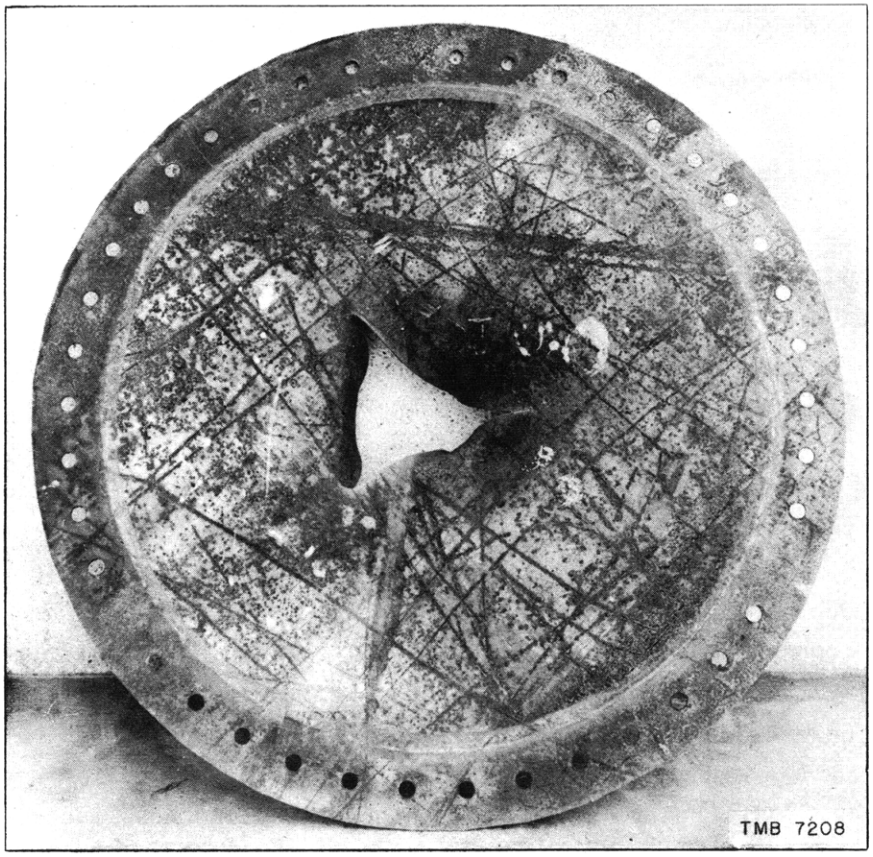


Figure 9a - Single-Plate 1/8-Inch Steel Diaphragm, Ruptured by Contact Charge of 1/2 Ounce of Tetryl

This is the water side of the diaphragm used in Test CT. It appears that the charge was not placed at the exact center of the plate. This 3-lobed fracture is different from the majority, which had 4 lobes.

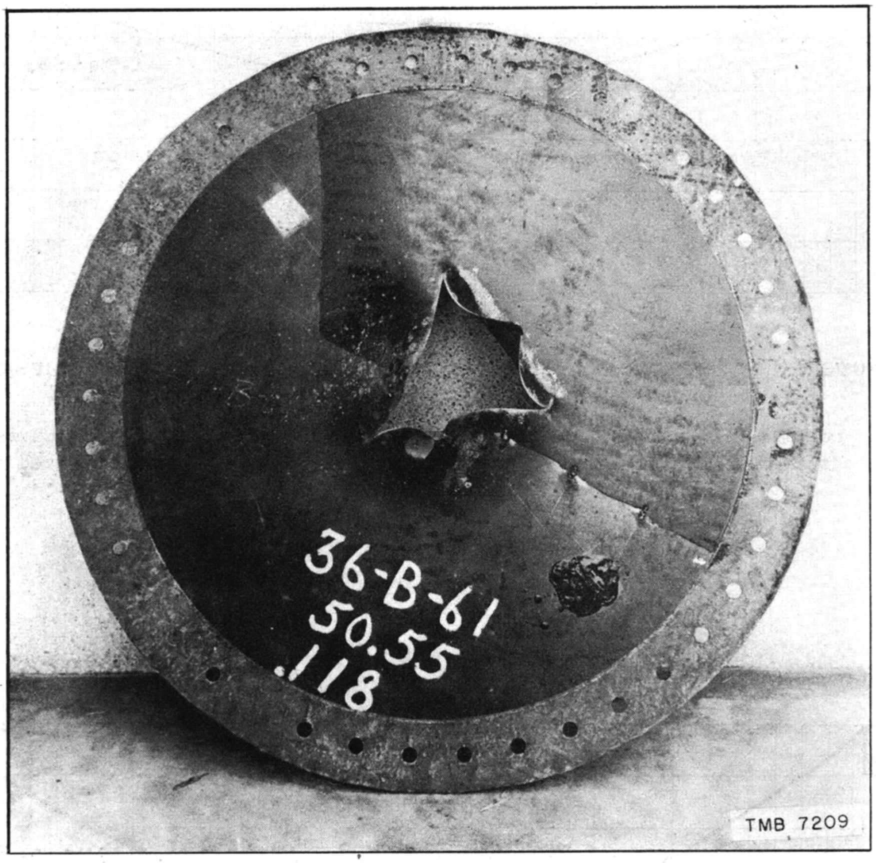


Figure 9b - Single-Plate 1/8-Inch Steel Diaphragm, Ruptured by Contact Charge of 1/2 Ounce of Tetryl

This is the outside or underside of the diaphragm, used in Test CT, away from the charge. Note the strain figures and the elongation in way of the bolt holes at the bottom and at the left side of the diaphragm.

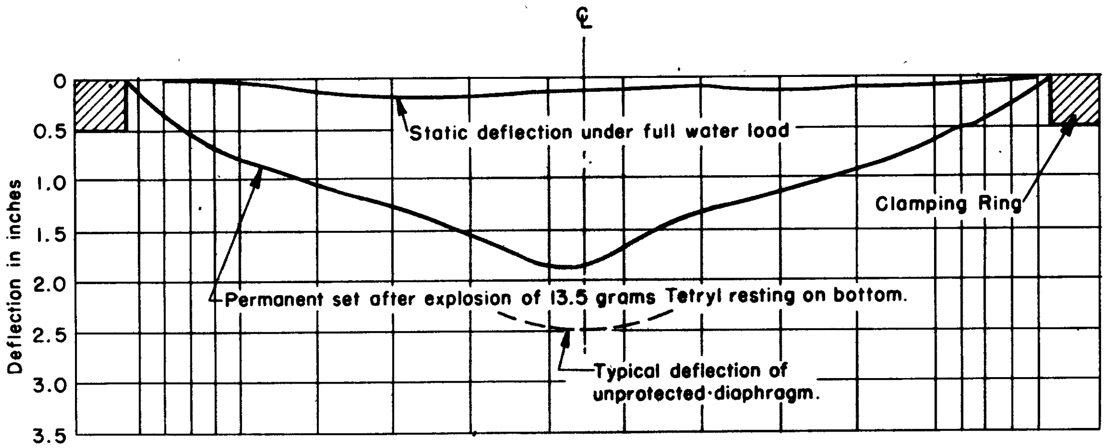


Figure 10 - Permanent Deflection Curve for Backing Diaphragm of Test BL-1

The irregular contour of the backing diaphragm under water load is probably due to irregularities in the steel itself, although irregularities in the filling material, plywood in this case, may have been a contributing factor.

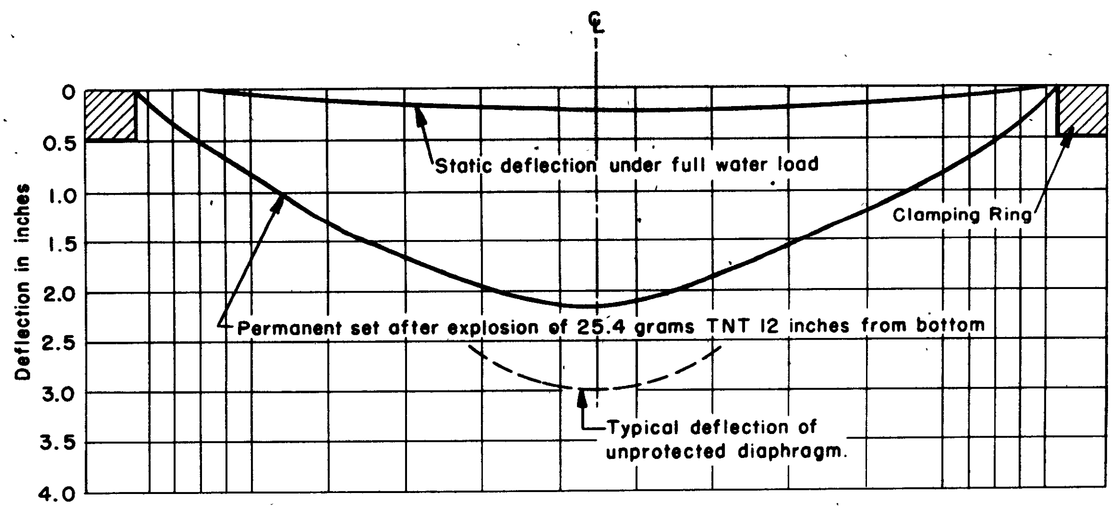


Figure 11 - Permanent Deflection Curve for Backing Diaphragm of Test R-1

The details of construction of this assembly appear in Table 4 on page 33. The shape is typical for a non-contact attack.

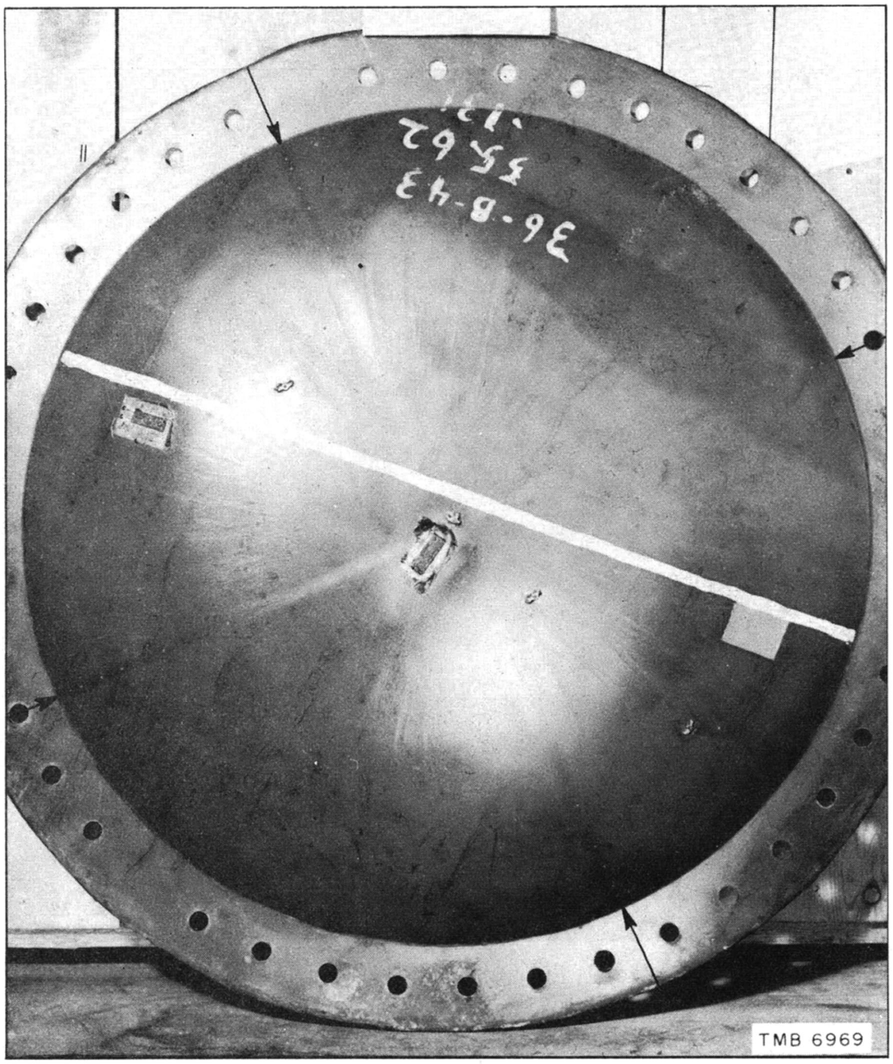


Figure 12 - Backing Diaphragm of Composite Structure, Test BW, after 3 Contact Explosions against the Facing Diaphragm

This shows the outside or underside of the diaphragm, with two metalectric strain gages still in place. The shape of the diaphragm was measured across the two diameters indicated by the arrows. Note the radial regions of concentrated strain.

Figure 13 - Typical Rupture in 1/32-Inch Facing Diaphragm

This diaphragm was from Test DH, shown in Table 7, Part 4, page 42. The charge was 1 ounce of tetryl in contact; practically all other contact charges were 1/2 ounce. This is the side of the facing diaphragm away from the explosion. There was in this test a 2-inch air space on this side between the facing and backing diaphragms.

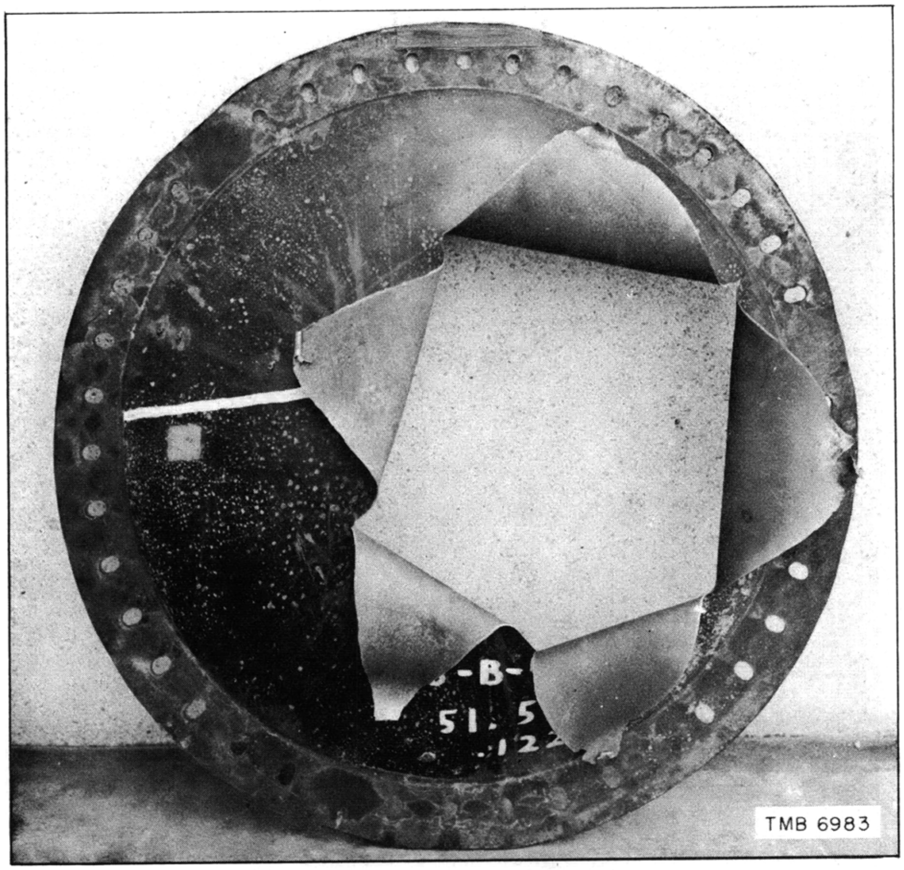


Figure 14 - Unique Case of Rupture of Single-Plate Reference Diaphragm

This diaphragm was used in Test CB, Table 2, page 30. This diaphragm was attacked successively by six 1-ounce charges of tetryl. The distance was 12 inches for the first three shots, then 6 inches, 3 inches, and 0 inches for the final three. The rupture occurred on the last shot.

Note the elongation in all the clamping-bolt holes.

Figure 15 - Typical Effect on Energy-Dissipative Material in a Composite Structure

The structure of this assembly is shown schematically in Table 9, page 53, opposite Test BM. Two charges of 1/2 ounce of tetryl were fired in succession in contact with the facing diaphragm. The facing diaphragm was 1/32 inch thick, and, with the charge, was placed on the near side of the 1-inch layer of roofing asphalt shown here. The rim of the 1/8-inch backing diaphragm appears around the asphalt.

The merit factor of this assembly was about 0.6.

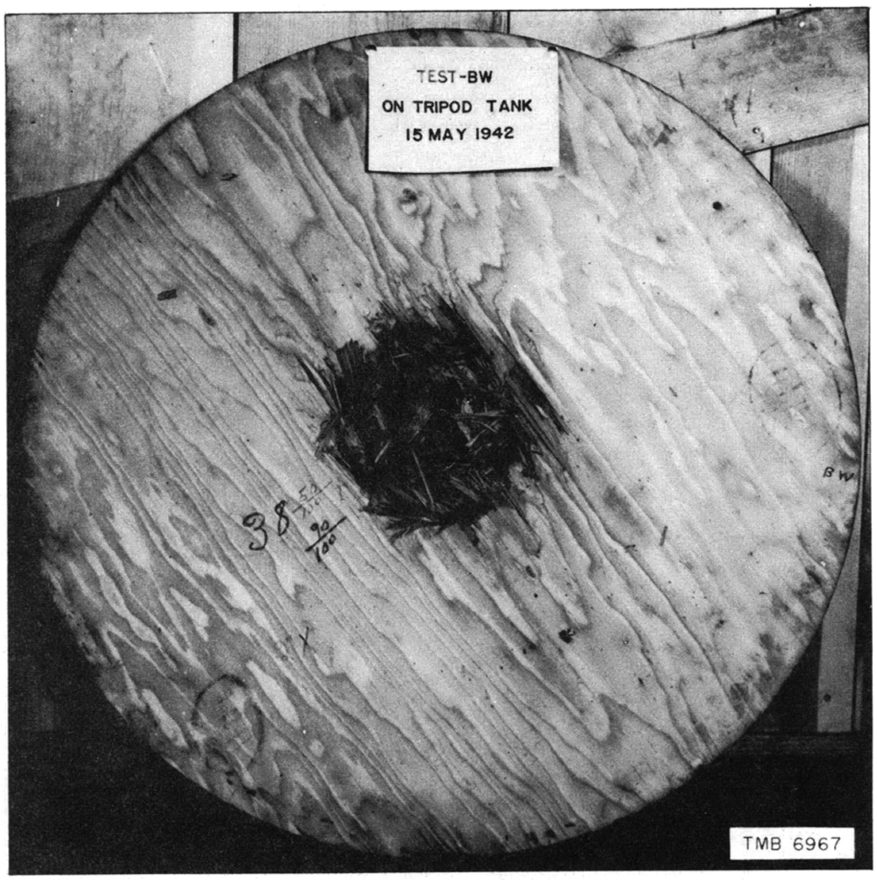


Figure 16 - Effect of a Contact Explosion on a 2-Inch Plywood Filling

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test BW. Each of the 3 charges fired was 1/2-ounce of tetryl, fired against a 1/32-inch facing diaphragm placed on the near side of the wood. This piece of plywood was merely a filler between the facing and backing diaphragms, and was not clamped at the edges.

The merit factor of this assembly was about 0.9.

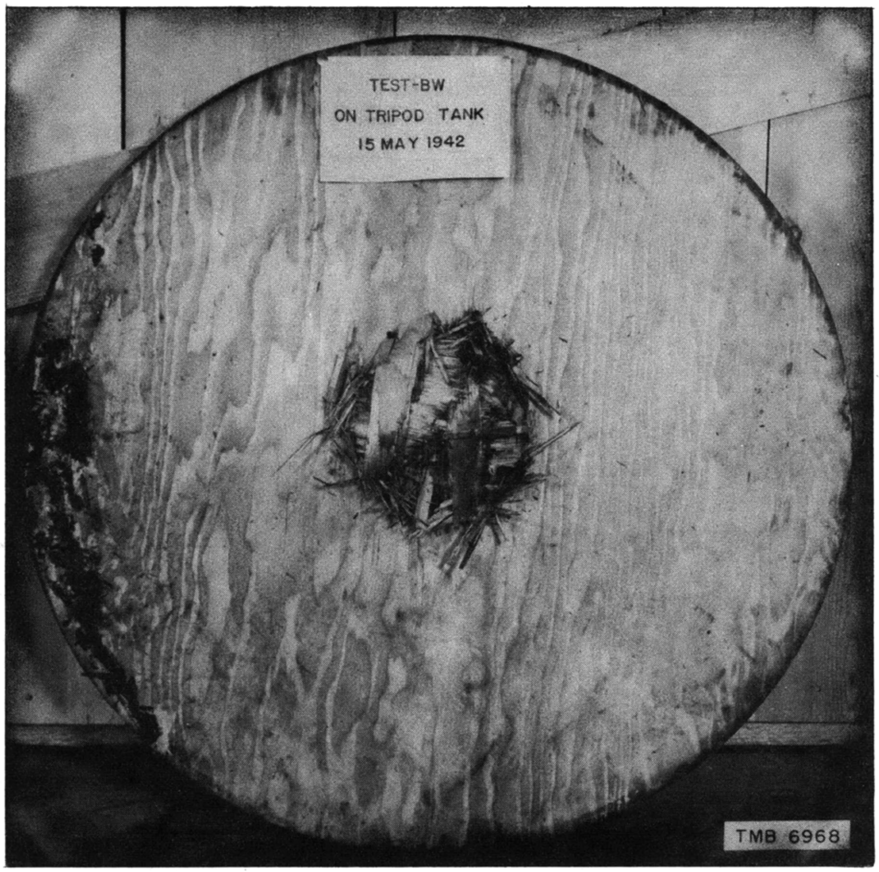


Figure 17 - Effect of a Contact Explosion on a 2-Inch Plywood Filling, Showing Damage on the Side Opposite to the Charge

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test BW. Each of the 3 charges fired was 1/2 ounce of tetryl, fired in contact with a 1/32-inch facing diaphragm on the far side of this filling piece. Note the shredding effect on the wood.

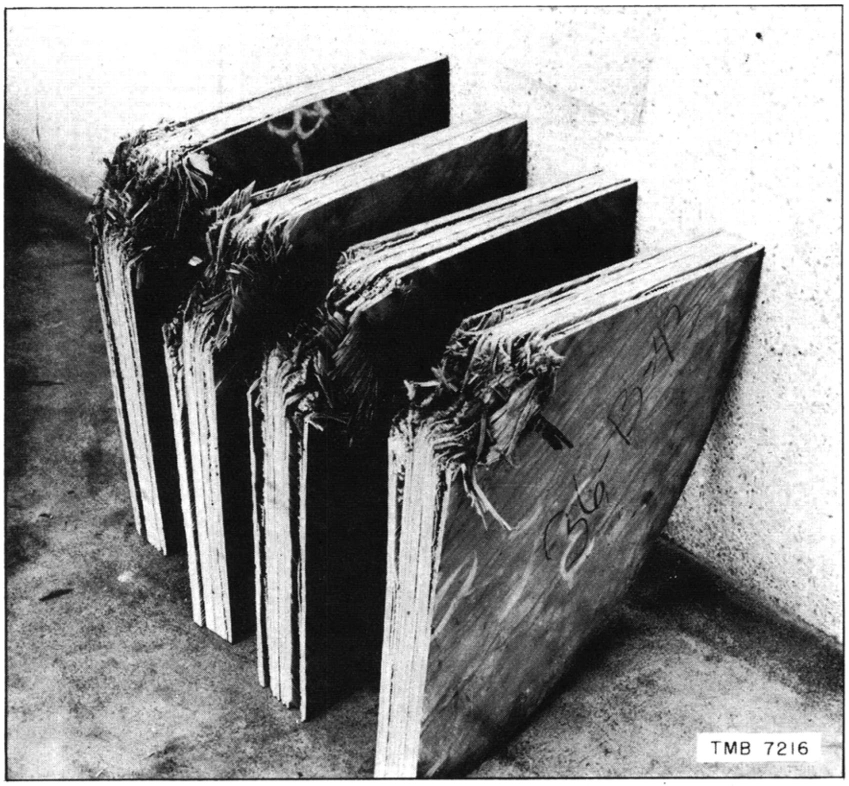


Figure 18 - Sections of 2-Inch Plywood Filling after Test BW

This is the plywood filler shown in Figures 16 and 17, sawed in four pieces to show the internal damage. Each of the 3 charges fired was 1/2 ounce of tetryl, fired against a 1/32-inch facing diaphragm on the far side of the filler.

Figure 19 - Effect of a Contact Explosion on a 1-Inch Clamped Plywood Layer in Combination with an Air Space

The structure of this assembly is shown schematically in Table 19, page 80, opposite Test DN. The side of the plywood away from the charge is shown here; there was a 1/32-inch facing diaphragm on the far side and a 2-inch air space followed by the 1/8-inch backing diaphragm on the near side. The charge was 1/2 ounce of tetryl in contact. Note that the shredding effect is well distributed.

The merit factor of this assembly was greater than 3.0.

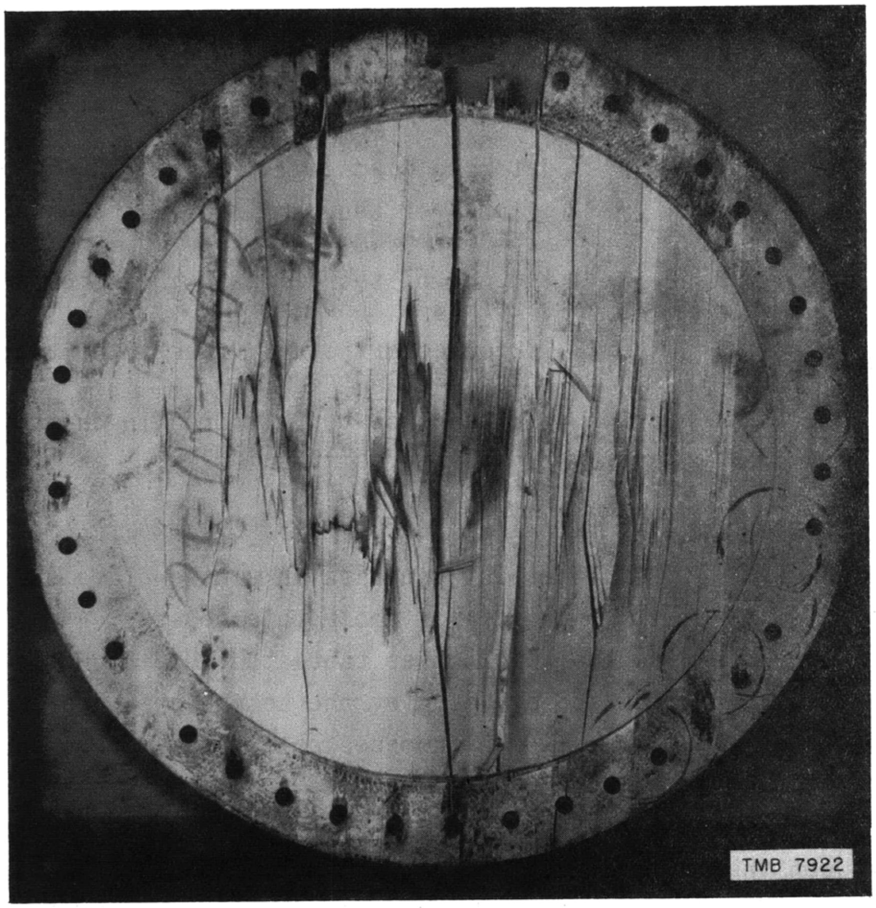


Figure 20 - Effect of a Distant Explosion on a Layer of 1-Inch Basswood in Combination with an Air Space

The structure of this assembly is shown schematically in Table 19, page 80, opposite Test EH. The charge was 1 ounce of tetryl, fired at 12 inches distance. On the far side of this layer was a 1/32-inch facing diaphragm; on the near side, was a 2-inch air space followed by the 1/8-inch backing diaphragm.

The merit factor of this assembly was greater than 3.5.

TEST CONFIGURATIONS

The tests may be divided conveniently into two classes, in each of which there are six groups or configurations. The two classes comprise those with the single-plate reference diaphragms and those with the composite protective assemblies. The six groups or configurations may be listed and identified as follows:

Configuration A - Shot 1 - 1 ounce of TNT fired at 12 inches above the flat diaphragm

Configuration B - Shot 2 - 1 ounce of TNT fired at 12 inches above the deformed diaphragm

Configuration C - Shot 1 - 1 ounce of tetryl fired 12 inches above the flat diaphragm

Configuration D - Shot 2 - 1 ounce of tetryl fired 12 inches above the deformed diaphragm

Configuration E - Shot 1 - 1/2 ounce of tetryl fired in contact with the flat diaphragm

Configuration F - Shot 2 - 1/2 ounce of tetryl fired in contact with the deformed diaphragm

TEST DATA ON REFERENCE DIAPHRAGMS

Tables 1, 2, and 3 present the data on single-plate steel diaphragms of various thicknesses, in the order of their thicknesses.

In these tables the thicknesses tabulated were found by weighing the entire diaphragm plate and dividing by the actual area and the weight per cubic inch of the material. The thicknesses so derived were checked by micrometer measurements around the edge.

The increase in deflection for the first shot is taken as the difference between the original deflection with water in the tank, and the residual maximum, observed at or near the center, after firing the first shot. The increase in deflection for the second shot is found by subtracting the deflection after the first shot from the deflection after the second shot. These maximum values were always used even though the maximum did not occur exactly at the center, as shown in the lower diagram of Figure 8 on page 13.

The increase in area ΔA was calculated by dividing the area of the diaphragm plate inside the clamping rings into annular conical rings, whose shape and dimensions could be determined from the contour measurements described on page 12, and then computing the area of each such conical ring. The summation of these areas, less the original area before the shot, gave the quantity desired. The same procedure was followed for determining the increase in area due to the second shots, except that in this case the first summation was subtracted from the second.

TABLE 1

Test Data on Reference Diaphragms of Single Steel Plate

A charge of 1 ounce of TNT was exploded on the axis 12 inches distant. The 12-inch distance, here and in all following similar tables, was measured from the upper surface of the facing diaphragm to the center of the charge.

Test	Thickness h inches	Weight of Plate per Square Inch pounds	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
Shot 1, Configuration A					
EY-1*	0.060	0.0170	4.05	53.3	27800
F-1	0.122	0.0345	2.53	26.1	60600
G-1	0.122	0.0345	2.68	26.5	60600
BE-1	0.122	0.0345	2.37	20.6	47100
BJ-1	0.122	0.0345	2.70	27.9	47100
BF-1	0.123	0.0348	2.50	22.2	48600
W-1	0.125	0.0354	2.92	28.1	
BI-1	0.127	0.0359	2.75	28.7	40000
X-1	0.197	0.0558	1.80	15.1	48700
U-1	0.260	0.0736	1.96	12.2	32300
EZ-1	0.378	0.1070	1.52	7.2	35000
Shot 2, Configuration B					
F-2**	0.122	0.0345	0.90	18.7	60600
G-2	0.122	0.0345	0.63	16.2	60600
BE-2	0.122	0.0345	0.63	19.8	47100
BF-2	0.123	0.0348	0.45	16.8	48600
W-2	0.125	0.0354	0.84	18.6	
BI-2	0.127	0.0359	0.95	26.2	40000
X-2	0.197	0.0558	0.76	10.2	48700
U-2	0.260	0.0736	0.48	7.7	32300
EZ-2	0.378	0.1070	0.68	10.6	35000

* Throughout this report, the number appearing in the test designation indicates the shot.

** The charge was fired 13 inches from the diaphragm for Test F-2 only.

TABLE 2

Test Data on Reference Diaphragms of Single Steel Plate

A charge of 1 ounce of tetryl was exploded on the axis 12 inches distant.

Test	Thickness h inches	Weight of Plate per Square Inch pounds	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
Shot 1, Configuration C					
EW-1	0.034	0.0096	Diaphragm ruptured		37600
EK-1	0.060	0.0170	5.22	81.0	28700
EN-1	0.060	0.0170	4.75	64.4	28700
EJ-1	0.106	0.0300	3.58	41.7	36700
EB-1	0.124	0.0351	3.03	32.9	53500
CB-1	0.126	0.0357	3.13	32.2	45400
CN-1	0.126	0.0357	3.22	32.4	46800
BV-1	0.132	0.0374	3.30	37.4	43900
CF-1	0.188	0.0532	2.75	21.3	38100
CE-1	0.258	0.0730	2.30	17.0	43500
EU-1	0.259	0.0733	2.10	15.2	39200
EM-1	0.334	0.0945	1.76	10.7	42700
EP-1	0.340	0.0962	1.74	9.2	44400
EL-1	0.376	0.1063	1.70	8.4	36200
EO-1	0.384	0.1090	1.83	9.6	37400
Shot 2, Configuration D					
BJ-2	0.122	0.0345	0.75	25.0	47100
CB-2	0.126	0.0357	0.57	29.9	45400
CN-2	0.126	0.0357	0.51	26.9	46800
BV-2	0.132	0.0374	0.80	31.2	43900
CF-2	0.188	0.0532	0.55	21.5	38100
CE-2	0.258	0.0730	0.65	15.3	43500
EU-2	0.259	0.0733	0.64	11.4	39200
EM-2	0.334	0.0945	0.49	7.8	42700
EP-2	0.340	0.0962	0.66	8.0	44400
EL-2	0.376	0.1063	0.73	10.5	36200
EO-2	0.384	0.1090	0.67	11.0	37400
Shot 3					
BJ-3	0.122	0.0345	0.60	24.3	47100

TABLE 3

Test Data on Reference Diaphragms of Single Steel Plate

A charge of 1/2 ounce of tetryl was exploded in contact with the center of the plate.

Test	Thickness h inches	Weight of Plate per Square Inch pounds	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in²
Shot 1, Configuration E					
ES-1	0.100	0.0283	2.95	21.5	37400
ET-1	0.100	0.0283	2.99	22.7	37400
BH-1*	0.122	0.0345	2.10	19.4	46900
BK-1	0.122	0.0345	2.20	14.5	46900
BP-1*	0.132	0.0374	2.37	18.0	43900
BS-1	0.189	0.0535	2.18	11.3	51600
EX-1	0.189	0.0535	2.39	13.8	52200
BR-1	0.248	0.0702	1.81	9.1	41900
EV-1	0.256	0.0724	2.11	11.1	39700
ER-1	0.322	0.0911	1.51	6.1	41400
EQ-1	0.380	0.1075	1.65	5.4	37900
Shot 2, Configuration F					
ES-2	0.100	0.0283	Diaphragm ruptured		37400
ET-2	0.100	0.0283	1.32	22.6	37400
BH-2*	0.122	0.0345	1.05	12.9	46900
BK-2	0.122	0.0345	1.15	14.7	46900
BP-2*	0.132	0.0374	0.65	15.8	43900
BS-2	0.189	0.0535	0.97	10.9	51600
EX-2	0.189	0.0535	1.15**	8.9**	52200
BR-2	0.248	0.0702	0.94	8.9	41900
EV-2	0.256	0.0724	0.91	9.8	39700
ER-2	0.322	0.0911	0.78	7.4	41400
EQ-2	0.380	0.1075	0.83	5.4	37900

* In tests BH-1, BH-2, BP-1, and BP-2, the charges were fired, not in contact with the diaphragm but at 3, 1 1/2, 1, and 1 inches respectively. The resulting data were used in computing the merit factor based on an averaging analysis for energy absorption, but were not used in the other three methods.

** A small tear occurred in the diaphragm after the second shot but these quantities could still be measured.

The yield stress set down in Tables 1, 2, and 3 was determined in the usual manner from the drop of the beam* in a conventional tensile test of material cut from the same plate as the diaphragm.

As the backing diaphragms used for the great majority of single-plate and composite assemblies were approximately 1/8 inch thick, a number of repeat measurements were made with plates of this thickness to obtain a good statistical average.

TEST DATA ON COMPOSITE PROTECTIVE ASSEMBLIES

Tables 4, 5, and 6 show the results for the second class of composite assemblies, subdivided according to the weight, kind, and position of the charge. These tables are made up in the same general fashion as Tables 1, 2, and 3. Each pair or set of entries in the table, for each type and detail of composite construction, is supplemented by a diagram showing the arrangement of the assembly and the various elements composing it. The various assemblies are listed in the order in which they were tested, with the results of both shots together.

The increase in deflection ΔZ is the value for the backing diaphragm only, measured in the same way as for the single diaphragms, as described on page 28. The increase in area ΔA is likewise for the backing diaphragm only, measured as described previously.

The yield stress tabulated here is for the backing diaphragm only, taken at the drop of the beam in a conventional tensile test of a specimen cut from the same plate as the diaphragm.

For convenient reference, and for use in making comparisons later between the performances of various assemblies, a value of thickness is given, equal to that of a single-steel diaphragm which would have the same weight as the entire composite assembly.

MISCELLANEOUS TEST DATA

In Table 7 is given a complete list of all the tests made on this project in chronological order, together with the other pertinent data not listed elsewhere, as indicated in the column headings.

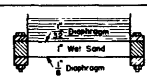
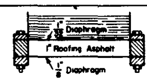
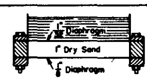
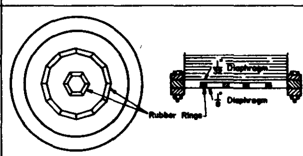
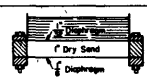
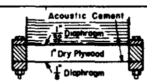
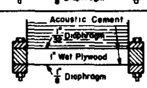
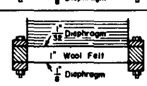
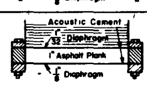
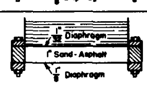
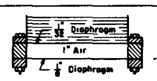
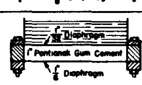
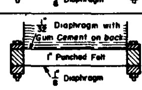
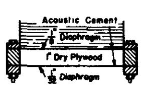
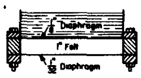
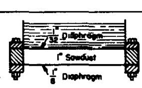
(Text continued on page 43)

* Throughout this report "drop-of-beam yield stress" refers to the stress computed by dividing the load at the first maximum in the load-elongation curve by the original area of the tensile specimen. This curve was recorded automatically by a Baldwin-Southwark load-strain recorder.

TABLE 4

Test Data on Composite Protective Assemblies

A charge of 1 ounce of TNT was exploded on the axis 12 inches distant. Configurations A and B.

Test	Schematic Assembly Diagram**	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_q of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
H-1		0.1073	0.379	2.33	17.2	60600
H-2		0.1073	0.379	0.53	12.9	60600
N-1		0.0911	0.322	2.17	14.4	56100
N-2		0.0911	0.322	0.63	11.8	56100
O-1		0.1152	0.407	2.37	15.8	56100
O-2		0.1152	0.407	0.55	11.9	56100
P-1		0.0446	0.158	2.19	13.7	56100
P-2		0.0446	0.158	0.58	8.0	56100
Q-1		0.1161	0.410	2.26	15.3	56100
Q-2		0.1161	0.410	0.51	12.7	56100
R-1		0.0667	0.236	2.00	12.0	65800
R-2		0.0667	0.236	0.76	12.3	65800
S-1		0.0689	0.243	2.11	13.4	56100
S-2		0.0689	0.243	0.85	13.7	56100
T-1		0.0470	0.166	2.15	14.0	48000
T-2		0.0470	0.166	0.73	12.7	48000
V-1		0.0993	0.351	2.08	14.5	49000
V-2		0.0993	0.351	0.76	12.6	49000
Y-1		0.1183	0.418	2.41	16.9	51000*
Y-2		0.1183	0.418	0.48	14.7	51000*
Z-1		0.0418	0.148	2.26	16.2	51000*
Z-2		0.0418	0.148	0.74	11.5	51000*
BA-1		0.0876	0.310	2.67	22.2	51000*
BA-2		0.0876	0.310	0.85	21.5	51000*
BB-1		0.0583	0.206	2.36	20.7	51000*
BB-2		0.0583	0.206	1.07	18.0	51000*
BC-1		0.0743	0.263	2.15	15.0	46100
Thin Backing Diaphragm		0.0743	0.263	2.23	14.55	23100
BD-1		0.0589	0.208	2.76	20.1	45900
Thin Backing Diaphragm		No data	No data	No data	No data	No data
BG-1		0.0476	0.168	2.05	11.9	45900
BG-2		0.0476	0.168	0.50	12.0	45900

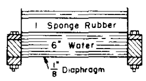
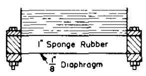
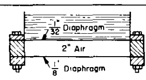
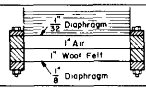
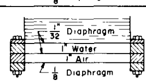
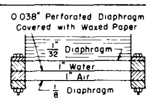
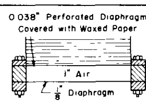
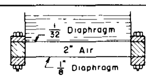
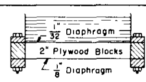
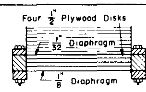
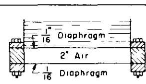
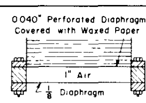
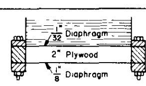
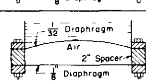
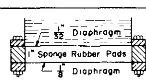
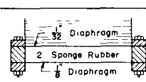
* σ_y was not measured for these cases; the average value for the control diaphragms, 51,000 pounds per square inch, was used because the control diaphragms came from the same lots of steel as the backing diaphragms.

** These and the similar diagrams in all following tables are not drawn to scale. The diaphragm thicknesses shown are only the nominal values, but the equivalent thicknesses, h_q, were derived from accurate weights by using 0.283 pound per square inch as the density of steel.

TABLE 5

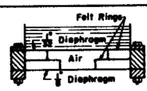
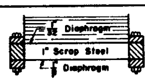
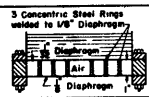
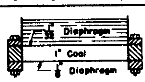
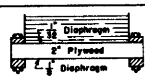
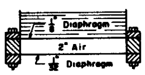
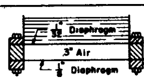
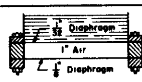
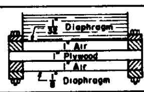
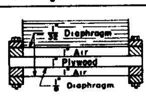
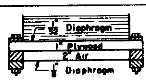
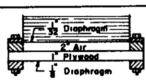
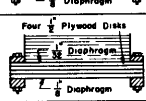
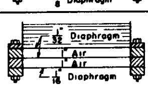
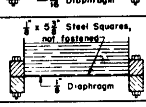
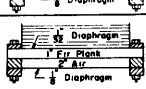
Test Data on Composite Protective Assemblies

A charge of 1 ounce of tetryl was exploded on the axis 12 inches distant, Configurations C and D.

Test	Schematic Assembly Diagram	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_q of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
BT-1*		0.0436	0.154	2.78	28.2	41700
BT-2*		0.0436	0.154	0.12	9.6	41700
BU-1*		0.0431	0.152	3.00	32.3	41700
BU-2*		0.0431	0.152	0.70	26.8	41700
CC-1		0.0424	0.150	2.48	13.4	50000
CC-2		0.0424	0.150	1.20	34.9	50000
CD-1		0.0488	0.172	2.50	14.5	50000
CD-2		0.0488	0.172	0.47	16.0	50000
CG-1		0.0865	0.306	2.60	13.8	46800
CG-2		0.0865	0.306	0.38	12.9	46800
CH-1		0.0804	0.284	2.20	10.0	46800
CI-1		0.0428	0.151	2.82	24.0	45400
CJ-1		0.0422	0.149	2.69	15.1	48000
CK-1		0.0814	0.288	2.76	22.5	48000
CK-2		0.0814	0.288	0.59	21.9	48000
CL-1		0.0869	0.307	2.30	17.3	43900
CL-2		0.0869	0.307	0.69	13.0	43900
CQ-1		0.0352	0.124	2.39 outer plate	11.4 outer plate 32.0 inner plate	24200
CR-1		0.0447	0.158	2.21	22.6	46400
CS-1		0.0870	0.307	2.17	14.4	43900
CS-2		0.0870	0.307	0.77	11.8	43900
CW-1		0.0416	0.147	2.37	20.1	43800
CX-1		0.0596	0.211	2.74	21.0	45200
CX-2		0.0596	0.211	0.41	19.4	45200
CY-1		0.0664	0.235	2.51	15.8	44200
CY-2		0.0664	0.235	0.69	14.5	44200

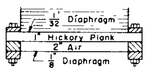
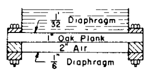
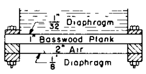
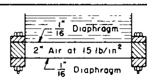
(continued)

TABLE 5 (continued)

Test	Schematic Assembly Diagram	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_e of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in²
CZ-1 CZ-2		0.0494 0.0494	0.175 0.175	2.52 0.68	15.0 14.4	43500 43500
DA-1 DA-2		0.1902 0.1902	0.672 0.672	2.92 0.38	22.3 19.9	46400 46400
DB-1		0.0595	0.210	2.78	17.8	43300
DC-1 DC-2		0.0825 0.0825	0.292 0.292	2.77 0.53	20.9 19.5	46000 46000
DD-1		0.0847	0.299	1.64	3.7 thin plate 10.9	46000
DE-1 Thin Backing Diaphragm		0.0439 0.0439	0.155 0.155	3.58 1.82	33.7 6.8	40000 25400
DF-1		0.0444	0.157	2.07	11.7	40000
DG-1		0.0460	0.163	2.99	22.3 thin plate torn	31800
DI-1		0.0655	0.231	1.53	6.4	31200
DL-1 Thin Backing Diaphragm		0.0744 0.0744	0.263 0.263	2.24 2.13	11.4 7.2	31600 21600
DM-1		0.0656	0.232	1.87	9.5	33400
DW-1		0.0636	0.225	1.94	9.0	43100
DX-1**		0.0884	0.312	1.42	4.6	60700
DZ-1		0.0351	0.124	2.65	14.8 outer plate 39.8 center plate 62.0 inner plate	25200
ED-1		0.0613	0.217	3.87	41.7	36800
EE-1		0.0579	0.205	1.87	8.5 44.0 inner plate	36800

(continued)

TABLE 5 (continued)

Test	Schematic Assembly Diagram	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_q of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
EF-1		0.0670	0.237	1.53	4.3 37.0 inner plate	37000
EG-1		0.0681	0.241	1.63	6.4 32.0 inner plate	37000
EH-1		0.0570	0.201	1.65	5.7	36700
EI-1		0.0348	0.123	1.42	12.2 34.0 inner plate	29800

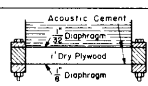
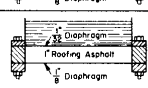
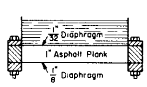
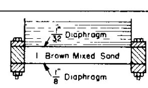
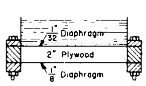
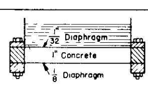
* For Tests BT-1, BT-2, BU-1, and BU-2 the charge was placed 12 inches above the original position of the backing diaphragm.

** The four plywood disks in Test DX were glued with the grain of each disk turned 22 1/2 degrees from the grain of the adjacent one.

TABLE 6

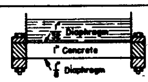
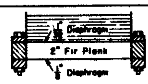
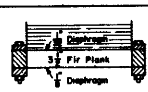
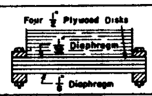
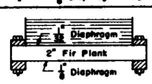
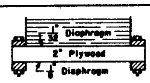
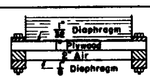
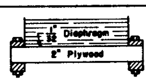
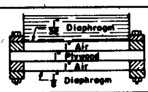
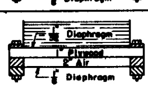
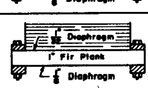
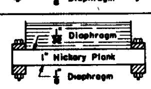
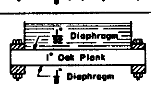
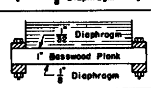
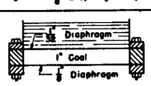
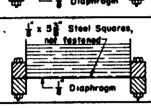
Test Data on Composite Protective Assemblies

A charge of 1/2 ounce of tetryl was exploded in contact with the center of the plate, Configurations E and F.

Test	Schematic Assembly Diagram	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_q of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in^2
BL-1		0.0668	0.236	1.70	8.1	34300
BL-2		0.0668	0.236	1.00	9.9	34300
BM-1		0.0899	0.318	2.25	13.3	34300
BM-2		0.0899	0.318	0.90	17.4	34300
BN-1		0.1035	0.366	1.50	12.7	40000
BN-2		0.1035	0.366	0.90	14.6	40000
BN-3		0.1035	0.366	0.65	8.8	40000
BO-1		0.1242	0.439	1.72	10.8	39000
BO-2		0.1242	0.439	0.50	9.4	39000
BW-1		0.0851	0.301	1.18	8.0	42400
BW-2		0.0851	0.301	0.95	9.4	42400
BW-3		0.0851	0.301	0.38	10.2	42400
BX-1*		0.1253	0.443	1.80	12.7	
BX-2*		0.1253	0.443	0.48	6.0	

(continued)

TABLE 6 (continued)

Test	Schematic Assembly Diagram	Weight of Test Structure per Square Inch of Area pounds	Equivalent Thickness h_e of Single Steel Plate of Equal Weight per Unit Area inches	Increase in Deflection ΔZ inches	Increase in Area ΔA square inches	Yield Stress σ_y lb/in²
BY-1* BY-2*		0.0930 0.0930	0.329 0.329	1.69 0.55	10.4 5.0	
BZ-1 BZ-2		0.0801 0.0801	0.283 0.283	0.98 1.27	2.4 7.3	42400 42400
CA-1 CA-2 CA-3		0.1042 0.1042 0.1042	0.368 0.368 0.368	0.58 0.46 1.26	4.7 4.2 12.8	45400 45400 45400
CM-1 CM-2		0.0868 0.0868	0.307 0.307	1.11 1.23	3.2 8.6	46800 46800
CO-1 CO-2		0.0709 0.0709	0.251 0.251	1.15 1.20	3.2 9.2	50900 50900
CP-1 CP-2		0.0866 0.0866	0.306 0.306	0.89 1.23	2.1 7.2	50400 50400
CU-1		0.0678	0.240	1.00	1.8	49000
CV-1		0.0503	0.178	**	**	**
DK-1		0.0659	0.233	1.31	2.4	30700
DN-1		0.0658	0.233	1.34	3.2	32800
DO-1		0.0638	0.225	2.12	11.8 thin plate 12.5	31800
DP-1		0.0728	0.257	1.74	5.6	30900
DQ-1		0.0730	0.258	1.66	5.0	33600
DR-1		0.0618	0.218	2.28	8.6	33900
DY-1		0.0876	0.310	1.01	6.8	53500
EC-1		0.0645	0.228	2.62	21.2	43100

* Pea gravel was used in the aggregate for the concrete filler in Tests BX-1 and BX-2. A special aggregate was used in the concrete filler for Tests BY-1 and BY-2.

** These quantities were not measured since no backing diaphragm was used and the facing diaphragm was ruptured.

TABLE 7

Additional Results of Observation on All Diaphragms, in Chronological Order

Part 1 - TNT Charges of 1 Ounce 12 Inches from the Facing or Reference Diaphragm, Configurations A and B

Test	Date of Test	Nominal Thickness and Type of Diaphragm	Actual Charge Weight grams	Maximum Explosion Pressure in Water lb/in²	Maximum Hoop Strain in/in × 10⁵	Maximum Diaphragm Strain in/in × 10⁵	Distance of Diaphragm Strain Gage from Center inches	Yield Strength lb/in²: Drop of Beam	Yield Strength lb/in²: Average for Plastic Range+
F-1	16-17 Jan 42	1/8-inch reference	24.0	2840			3/8	60600	61800
*F-2	16-17 Jan 42	1/8-inch reference	24.0	1780	84		3/8	60600	62500
F-5	16-17 Jan 42	1/8-inch reference	23.1				3/8	60600	62900
G-1	21 Jan 42	1/8-inch reference	24.1	1740	99	650† Gage broke	3/8	60600	61800
G-2	21 Jan 42	1/8-inch reference	23.0		97		3/8	60600	62400
H-1	24 Jan 42	1/8-inch backing	24.0	1640			3/8	60600	61500
H-2	24 Jan 42	1/8-inch backing	24.0		109		3/8	60600	61800
N-1	27 Jan 42	1/8-inch backing	23.1			600	1	56100	56700
N-2	27 Jan 42	1/8-inch backing	23.1				1	56100	57300
O-1	29 Jan 42	1/8-inch backing	24.1	1580	66	760 Gage broke	1	56100	56700
O-2	29 Jan 42	1/8-inch backing	24.0		60		1	56100	58500
P-1	2 Feb 42	1/8-inch backing	24.0	1940	108	900	1	56100	57300
P-2	2 Feb 42	1/8-inch backing	26.5	2310	92	650	1	56100	57900
Q-1	4 Feb 42	1/8-inch backing	26.0		101	390	1	56100	57300
Q-2	4 Feb 42	1/8-inch backing	24.9	1680	110	270	1	56100	58400
R-1	6 Feb 42	1/8-inch backing	25.4	1970	110	570	1	65800	66200
R-2	6 Feb 42	1/8-inch backing	27.5	1970	120	840 Gage broke	1	65800	66800
S-1	10 Feb 42	1/8-inch backing	27.4	1600	112	1760 } Gage broke	1	56100	57300
S-2	10 Feb 42	1/8-inch backing	26.5	1780		500 }	1	56100	58200
T-1	12 Feb 42	1/8-inch backing	28.2		104		1	48000	49200
T-2	12 Feb 42	1/8-inch backing	28.1	1850	116	640 Gage broke	1	48000	46400
U-1	14 Feb 42	1/4-inch reference	27.1	1570	106	680 Gage broke	1	32300	32300
U-2	14 Feb 42	1/4-inch reference	26.6	1560	102**	Gage off	1	32300	32300
V-1	17 Feb 42	1/8-inch backing	26.5	2470	129	570	1	49000	49900
V-2	17 Feb 42	1/8-inch backing	25.4	2350	101	690 Gage broke	1	49000	51600
W-1	19 Feb 42	1/8-inch reference	28.5	2170	109	680	1		
W-2	19 Feb 42	1/8-inch reference	26.7	1610			1		
X-1	21 Feb 42	3/16-inch reference	26.9	1630	102	510	1	48700	48700
X-2	21 Feb 42	3/16-inch reference	28.0	1320		Gage off	1	48700	54500
Y-1	24 Feb 42	1/8-inch backing	27.6			Gage off	1	51000††	
Y-2	24 Feb 42	1/8-inch backing	28.4	1670	114	Gage off	1	51000††	
Z-1	26 Feb 42	1/8-inch backing	27.3	1530	123	290 Gage off	1	51000††	
Z-2	26 Feb 42	1/8-inch backing	27.9	1950	106	Gage off	1	51000††	
BA-1	28 Feb 42	1/8-inch backing	26.0	1860	123	Gage off	1	51000††	
BA-2	28 Feb 42	1/8-inch backing	28.3	2010	103	Gage off	1	51000††	
BB-1	3 Mar 42	1/8-inch backing	26.6	1490	142	860	1	51000††	
BB-2	3 Mar 42	1/8-inch backing	27.0	1770	125	Gage off	1	51000††	
BC-1	6 Mar 42	1/32-inch backing	27.7	1790			1	23100	
BD-1	10 Mar 42	1/32-inch backing	27.9	1950	121**		1		
BE-1	12 Mar 42	1/8-inch reference	27.0	1900	101**		1	47100	48700
BE-2	12 Mar 42	1/8-inch reference	26.5	2000	106**		1	47100	52900
BF-1	13 Mar 42	1/8-inch reference	26.8	1910	123	750	1	48600	51600
BF-2	13 Mar 42	1/8-inch reference	26.8	1930	95		1	48600	56800
BG-1	20 Mar 42	1/8-inch backing	27.6	1510	103	550	9 1/2	45900	46500
BG-2	20 Mar 42	1/8-inch backing	26.1	1700	119	560	9 1/2	45900	47900
BI-1	6 Apr 42	1/8-inch reference	26.9			1400	9 1/2	40000	40000
BI-2	6 Apr 42	1/8-inch reference	27.0		111	530	9 1/2	40000	40400
BJ-1	10 Apr 42	1/8-inch reference	28.8		95		9 1/2	47100	49400
EY-1	16 Mar 43	1/16-inch reference	26.5					27800	33300
EZ-1	16 Mar 43	3/8-inch reference	26.5					35000	35000
EZ-2	16 Mar 43	3/8-inch reference	26.5					35000	35900

* For Test F-2 the charge was placed 13 inches from the diaphragm.

** These are average values from two gages.

† Throughout this table any values of maximum diaphragm strain quoted with the comment "gage broke" or "gage off" indicates only the value for strain when the gage actually broke or came loose, not the true maximum strain which presumably came later.

†† σ_y was not measured for these cases; the average value for the control diaphragms, 51,000 pounds per square inch, was used because the control diaphragms came from the same lots of steel as the backing diaphragms.

\+ The yield strength quoted in the final column exceeds that recorded in Tables 1 to 6 by a small amount. This difference arose in an attempt to account for the strain-hardening of the metal, especially in its effect in raising the stress value against which the plastic flow occurred at the second shots.

TABLE 7 (continued)

Part 2 - Tetryl Charges of 1 Ounce 12 Inches from the Facing or Reference Diaphragm, Configurations C and D

Test	Date of Test	Nominal Thickness and Type of Diaphragm	Actual Charge Weight grams	Maximum Explosion Pressure in Water lb/in^2	Maximum Hoop Strain $in/in \times 10^5$	Maximum Diaphragm Strain $in/in \times 10^5$	Distance of Diaphragm Strain Gage from Center inches	Yield Strength lb/in^2 Drop of Beam	Yield Strength lb/in^2 Average for Plastic Range
BJ-2	10 Apr 42	1/8-inch reference	26.1	1700	109†		9 1/2	47100	59400
BJ-3	10 Apr 42	1/8-inch reference	26.8		77		9 1/2	47100	63400
BT-1*	8 May 42	1/8-inch backing	27.1	1980	101	600	13 1/2	41700	42000
BT-2*	8 May 42	1/8-inch backing	26.2	1440**	59	260	13 1/2	41700	41900
BU-1*	11 May 42	1/8-inch backing	27.1	1860	132	710	13 1/2	41700	42000
BU-2*	11 May 42	1/8-inch backing	26.3	2720	134	530	13 1/2	41700	42600
BV-1	13 May 42	1/8-inch reference	27.2	2520	125	1800	9	43900	42300
BV-2	13 May 42	1/8-inch reference	26.7	2010	116	1300	9	43900	43400
CB-1	27 May 42	1/8-inch reference	26.9	3140	143	1500	0	45400	47400
CB-2	27 May 42	1/8-inch reference	27.8	2220	142	760	13	45400	50100
CC-1	29 May 42	1/8-inch backing	25.7	2280		2000	0	50000	50800
CC-2	29 May 42	1/8-inch backing	26.6	1500			0	50000	54200
CD-1	1 Jun 42	1/8-inch backing	26.7			660	0	50000	51300
CD-2	1 Jun 42	1/8-inch backing	26.1			720	0	50000	54200
CE-1	3 Jun 42	1/4-inch reference	26.9	1110	162	1600	0	43500	40800
CE-2	3 Jun 42	1/4-inch reference	26.9	680	144		0	43500	41700
CF-1	6 Jun 42	3/16-inch reference	26.9	2400	162	160	13	38100	42100
CF-2	6 Jun 42	3/16-inch reference	26.9	1950	132	820	13	38100	47900
CG-1	8 Jun 42	1/8-inch backing	26.8	2330	137	350	0	46800	48400
CG-2	8 Jun 42	1/8-inch backing	26.1	2120	131		0	46800	52200
CH-1	10 Jun 42	1/8-inch backing	26.4	1390			0	46800	47900
CI-1	12 Jun 42	1/8-inch backing	26.8	2500		330	13	45400	49000
CJ-1	15 Jun 42	1/8-inch backing	27.0	1970	132			48000	51000
CK-1	17 Jun 42	1/8-inch backing	27.6		146	520	0	48000	51600
CK-2	17 Jun 42	1/8-inch backing	26.3	2000	131	600	0	48000	56000
CL-1	19 Jun 42	1/8-inch backing	26.8		138	350	13	43900	47000
CL-2	19 Jun 42	1/8-inch backing	28.9	1840	135	320	13	43900	50600
CN-1	24 Jun 42	1/8-inch reference	26.6		135			46800	49500
CN-2	24 Jun 42	1/8-inch reference	26.5		126			46800	53700
CQ-1	2 Jul 42	1/16-inch backing	25.5				1	24200	25100
CR-1	4 Jul 42	1/8-inch backing	25.5		Greater than 50		1	46400	47900
CS-1	7 Jul 42	1/8-inch backing	25.5		127		1	43900	44700
CS-2	7 Jul 42	1/8-inch backing	25.5		125	170	1	43900	46500
CW-1	16 Jul 42	1/8-inch backing	25.5					43800	43900
CX-1	18 Jul 42	1/8-inch backing	25.5				13	45200	47400
CX-2	18 Jul 42	1/8-inch backing	25.5		145	620	13	45200	52400
CY-1	21 Jul 42	1/8-inch backing	25.5			260	13	44200	46100
CY-2	21 Jul 42	1/8-inch backing	25.5		114	340	13	44200	49900
CZ-1	23 Jul 42	1/8-inch backing	25.5			540	13	43500	44700
CZ-2	23 Jul 42	1/8-inch backing	25.5			440	13	43500	47600

(continued)

TABLE 7, Part 2 (continued)

Test	Date of Test	Nominal Thickness and Type of Diaphragm	Actual Charge Weight grams	Maximum Explosion Pressure in Water lb/in²	Maximum Hoop Strain in/in × 10^5	Maximum Diaphragm Strain in/in × 10^5	Distance of Diaphragm Strain Gage from Center inches	Yield Strength lb/in²	
								Drop of Beam	Average for Plastic Range
DA-1	26 Jul 42	1/8-inch backing	25.5	2360	146	780	13	46400	48700
DA-2	26 Jul 42	1/8-inch backing	25.5		114		13	46400	52600
DB-1	28 Jul 42	1/8-inch backing	25.5	2370	124		13	43300	44100
DC-1	31 Jul 42	1/8-inch backing	25.5	1690		420	13	46000	47900
DC-2	31 Jul 42	1/8-inch backing	25.5	2000		640	13	46000	51500
DD-1	4 Aug 42	1/8-inch backing	25.5		117	1250	0	46000	48300
DE-1	6 Aug 42	1/32-inch backing	25.5		133	210	13	25400	
DF-1	10 Aug 42	1/8-inch backing	25.5		127	690	0	40000	40400
DG-1	11 Aug 42	1/8-inch backing	25.5		112	440	13	31800	32700
DI-1	18 Aug 42	1/8-inch backing	25.5		175	280	13	31200	31600
DL-1	26 Aug 42	1/32-inch backing	25.5		158†	360	13	21600	
DM-1	28 Aug 42	1/8-inch backing	25.5		136	610	0	33400	34300
DW-1	22 Sep 42	1/8-inch backing	26.5		109	1520	0	43100	43600
DX-1	24 Sep 42	1/8-inch backing	26.5	2760	113	500	0	60700	61000
DZ-1	29 Sep 42	1/16-inch backing	26.5					25200	25700
EB-1	3 Oct 42	1/8-inch reference	26.5	3610	121	960	13	53500	54500
ED-1	8 Oct 42	1/8-inch backing	26.5	2960	112	Greater than 1700	13	36800	39000
EE-1	10 Oct 42	1/8-inch backing	26.5		85	390	13	36800	37200
EF-1	15 Oct 42	1/8-inch backing	26.5	2790	109	150	13	37000	37300
EG-1	17 Oct 42	1/8-inch backing	26.5	1920	117			37000	37500
EH-1	20 Oct 42	1/8-inch backing	26.5		120	290	13	36700	37000
EI-1	22 Oct 42	1/16-inch backing	26.5		130	350	13	29800	30200
EJ-1	24 Oct 42	1/8-inch reference	26.5					36700	39100
EK-1	13 Feb 43	1/16-inch reference	26.5					28700	30700
EL-1	17-18 Feb 43	3/8-inch reference	26.5					36200	36400
EL-2	19 Feb 43	3/8-inch reference	26.5					36200	39200
EM-1	19 Feb 43	5/16-inch reference	26.5					42700	43100
EM-2	19 Feb 43	5/16-inch reference	26.5					42700	43600
EN-1	23 Feb 43	1/16-inch reference	26.5					28700	30600
EO-1	24 Feb 43	3/8-inch reference	26.5					37400	37300
EO-2	24 Feb 43	3/8-inch reference	26.5					37400	39700
EP-1	26 Feb 43	5/16-inch backing	26.5					44400	44800
EP-2	26 Feb 43	5/16-inch backing	26.5					44400	46800
EU-1	10 Mar 43	1/4-inch reference	26.5					39200	40000
EU-2	10 Mar 43	1/4-inch reference	26.5					39200	41600
EW-1	12 Mar 43	1/32-inch reference	26.5					37600	

* For Tests BT-1, BT-2, BU-1, and BU-2 the charge was 12 inches above the original position of the backing diaphragm.

** This value was taken on the second peak.

† These are average values from two gages.

TABLE 7 (continued)

Part 3 - Tetryl Charges of 1/2 Ounce in Contact, Configurations E and F

Test	Date of Test	Nominal Thickness and Type of Diaphragm	Actual Charge Weight grams	Maximum Explosion Pressure in Water lb/in²	Maximum Hoop Strain in/in × 10⁵	Maximum Diaphragm Strain in/in × 10⁵	Distance of Diaphragm Strain Gage from Center inches	Yield Strength lb/in²	
								Drop of Beam	Average for Plastic Range
BH-1*	2 Apr 42	1/8-inch reference	13 1/4		64	620	9 1/2	46900	47900
BH-2*	2 Apr 42	1/8-inch reference	13 1/4				9 1/2	46900	51800
BH-3*	2 Apr 42	1/8-inch reference	13 1/4		49	410	9 1/2	46900	56100
BK-1	14 Apr 42	1/8-inch reference	13 1/4	2090	41		9 1/2	46900	47900
BK-2	14 Apr 42	1/8-inch reference	13 1/4	1730	43		9 1/2	46900	50700
BL-1	16 Apr 42	1/8-inch backing	13 1/4	1715	25	400	9 1/2	34300	34200
BL-2	16 Apr 42	1/8-inch backing	13 1/4		24	190	9 1/2	34300	34200
BM-1	18 Apr 42	1/8-inch backing	13 1/4	1760	48		9 1/2	34300	34200
BM-2	18 Apr 42	1/8-inch backing	13 1/4	1360	66		9 1/2	34300	34800
BN-1	21 Apr 42	1/8-inch backing	13 1/4	820	29	1140	13 1/2	40000	44200
BN-2	21 Apr 42	1/8-inch backing	13 1/4	1450	51		13 1/2	40000	44200
BN-3	21 Apr 42	1/8-inch backing	13 1/4						
BO-1	24 Apr 42	1/8-inch backing	13 1/4		26	380	13 1/2	39000	38300
BO-2	24 Apr 42	1/8-inch backing	13 1/4	1090	27	310	13 1/2	39000	38300
BP-1*	27 Apr 42	1/8-inch reference	13 1/4	1160		170	9 1/2	43900	42800
BP-2*	27 Apr 42	1/8-inch reference	13 1/4	1150			9 1/2	43900	42300
BR-1	1 May 42	1/4-inch reference	13 1/4	1680		720	13 1/2	41900	41900
BR-2	1 May 42	1/4-inch reference	13 1/4	1580		320	13 1/2	41900	41900
BS-1	4 May 42	3/16-inch reference	13 1/4	1820	40	380	13 1/2	51600	51600
BS-2	4 May 42	3/16-inch reference	13 1/4	1580	30	230	13 1/2	51600	54300
BW-1	15 May 42	1/8-inch backing	13 1/4	1340	30	1050	0	42400	42400
BW-2	15 May 42	1/8-inch backing	13 1/4	1160	26		0	42400	42200
BW-3	15 May 42	1/8-inch backing	13 1/4	1110	26	870	0	42400	42200
BX-1	18 May 42	1/8-inch backing	13 1/4	1570		1130	0		
BX-2	18 May 42	1/8-inch backing	13 1/4	1160			0		
BY-1	20 May 42	1/8-inch backing	13 1/4	1380			0		
BY-2	20 May 42	1/8-inch backing	13 1/4	1220	23	1420	0		
BZ-1	22 May 42	1/8-inch backing	13 1/4	1340	28	150	0	42400	42200
BZ-2	22 May 42	1/8-inch backing	13 1/4	1550	20		0	42400	42200
CA-1	25 May 42	1/8-inch backing	13 1/4	1390	42	220	0	45400	45600
CA-2	25 May 42	1/8-inch backing	13 1/4	1570	36	280	0	45400	46100
CA-3	25 May 42	1/8-inch backing	13 1/4	1530	50		0	45400	47100
CM-1	22 Jun 42	1/8-inch backing	13 1/4	1250	47			46800	46800
CM-2	22 Jun 42	1/8-inch backing	13 1/4	1080	38			46800	47400
CO-1	26 Jun 42	1/8-inch backing	13 1/4		30	850	1	50900	51800
CO-2	26 Jun 42	1/8-inch backing	13 1/4		27	190	1	50900	52200
CP-1	30 Jun 42	1/8-inch backing	13 1/4		39	220	1	50400	50600
CP-2	30 Jun 42	1/8-inch backing	13 1/4		38	830	1	50400	50800
CT-1	9 Jul 42	1/8-inch reference	13 1/4	1470	40	230	13	48000	
CU-1	11 Jul 42	1/8-inch backing	13 1/4					49000	49100

(continued)

TABLE 7, Part 3 (continued)

Test	Date of Test	Nominal Thickness and Type of Diaphragm	Actual Charge Weight grams	Maximum Explosion Pressure in Water lb/in²	Maximum Hoop Strain in/in × 10⁵	Maximum Diaphragm Strain in/in × 10⁵	Distance of Diaphragm Strain Gage from Center inches	Yield Strength lb/in²	
								Drop of Beam	Average for Plastic Range
CV-1	14 Jul 42	None	13 1/4	1290	42				
DK-1	24 Aug 42	1/8-inch backing	13 1/4		53**			30700	31000
DN-1	31 Aug 42	1/8-inch backing	13 1/4		37	660	0	32800	33200
DO-1	2 Sep 42	1/8-inch backing	13 1/4		74**			31800	32800
DP-1	4 Sep 42	1/8-inch backing	13 1/4		36	360	13	30900	31200
DQ-1	8 Sep 42	1/8-inch backing	13 1/4		50**	430	13	33600	34200
DR-1	10 Sep 42	1/8-inch backing	13 1/4		111	340	13	33900	34400
DY-1	26 Sep 42	1/8-inch backing	13 1/4			300	0	53500	53700
EC-1	6 Oct 42	1/8-inch backing	13 1/4	2130	36	410	13	43100	44100
EQ-1	1 Mar 43	3/8-inch reference	13 1/4					37900	38300
EQ-2	1 Mar 43	3/8-inch reference	13 1/4					37900	39200
ER-1	3 Mar 43	5/16-inch reference	13 1/4					41400	41400
ER-2	3 Mar 43	5/16-inch reference	13 1/4					41400	43100
ES-1	5 Mar 43	1/8-inch reference	13 1/4					37400	37800
ES-2	5 Mar 43	1/8-inch reference	13 1/4					37400	
ET-1	9 Mar 43	1/8-inch reference	13 1/4					37400	35600
ET-2	9 Mar 43	1/8-inch reference	13 1/4					37400	38200
EV-1	11 Mar 43	1/4-inch reference	13 1/4					39700	39600
EV-2	11 Mar 43	1/4-inch reference	13 1/4					39700	39700
EX-1	13 Mar 43	3/16-inch reference	13 1/4					52200	52800
EX-2	13 Mar 43	3/16-inch reference	13 1/4					52200	54200

* On Tests BH-1, BH-2, BH-3, BP-1, and BP-2 the charges were not fired in contact; see the footnote to Table 3. In Test BH-3 the charge was fired at a distance of 1 1/2 inch.

** These are average values from two gages.

TABLE 7 (continued)

Part 4 - Tetryl Charges of 1 Ounce in Contact

The seven cases mentioned in this table do not fall in any of the six standard configurations, but the data are included here for the sake of completeness.

Test	Date of Test	Nominal Thickness and Type of Diaphragm	Actual Charge Weight grams	Maximum Explosion Pressure in Water lb/in²	Maximum Hoop Strain in/in × 10⁵	Maximum Diaphragm Strain in/in × 10⁵	Distance of Diaphragm Strain Gage from Center inches	Yield Strength lb/in²	
								Drop of Beam	Average for Plastic Range
DH-1	13 Aug 42	1/8-inch backing	25.5	1400	94	210	1	32000	38700
DJ-1	20 Aug 42	1/4-inch reference	25.5		66*	1030	13	38800	40100
DS-1	12 Sep 42	1/8-inch backing	25.5					43100	43900
DT-1	15 Sep 42	1/8-inch backing	26.5	3260	57			57900	58300
DU-1	17 Sep 42	1/8-inch backing	25.5					57900	58300
DV-1	19 Sep 42	1/8-inch backing	25.5	2380	53	520	13	60700	61100
EA-1	1 Oct 42	1/8-inch backing	26.5	2200	61	420	13	57000	57400

* This is an average value from two gages.

GENERAL COMMENTS ON TEST RESULTS

The outstanding results of these tests may be set down briefly as follows, in advance of an analysis of any kind.

Except for assemblies containing wood, made up so as to clamp the wood at the edges, no composite structures were as effective as single steel plates of the equivalent weight per unit area. However, multiple-diaphragm constructions with air spaces proved effective; see Table 16 on page 76.

The composite assemblies containing sand were noticeably less effective than single steel plates of equivalent weight.

For the reference diaphragms made up of single plates, the maximum center deflections on the first shots varied from about 5 1/4 inches for plates 1/16 inch thick to about 1 3/4 inch for plates 3/8 inch thick. The corresponding increases in area varied from 81 to 9.6 square inches, representing percentage increases in area* from 7.9 to 0.95, for the 1/16-inch and the 3/8-inch plates respectively.

For the composite assemblies, the maximum center deflections of the backing diaphragms, in most cases of 1/8-inch plate, varied from 9/16 inch to 3 7/8 inches on the first shots, for equivalent single steel plate thicknesses of 0.368 to 0.217 inch, respectively. The corresponding increases in area of the backing diaphragms were 4.7 and 41.7 square inches; expressed in percentages, these were 0.46 and 4.1.

For successive shots, the increases in area of the diaphragms were of the same order, although there was a great deal of irregular variation, up to about 50 per cent. In a few cases the variation reached 200 per cent. In general, the increase in area on the first shot was larger than on any later shots.

The observed peak explosion pressures in the water at a distance of 16 inches from the charge varied from a maximum of 2840 pounds per square inch for 24.0 grams of TNT to 3610 pounds per square inch for 26.5 grams of tetryl. A peak pressure of 2130 pounds per square inch was recorded for 13.25 grams of tetryl.

A large and partly unexpected variation was found in the yield strengths of the various plates from which the reference and backing diaphragms were cut. This is perhaps no more than a natural consequence of the unavoidable use of whatever steel was available, over a long period of defense and war activity when steel was a critical material. Some plates showed a yield strength as low as 24,200 pounds per square inch, whereas

---

* The area of a diaphragm 36 inches in diameter is 1017.9 square inches.

others had a value as high as 65,800 pounds per square inch. The latter were of a type of high-tensile steel, which was used when no medium steel was immediately available.

METHODS OF ANALYZING DAMAGE

The simplest and most direct method of determining damage to a structure designed to resist underwater explosion is, of course, to observe whether or not it ruptures. In many previous tests this has been the only criterion used.

The next simplest method is to determine the amount of deflection that takes place in certain important members, which may lie relatively close to units which would be deranged or damaged by excessive deflection even though they were not flooded. A case in point would be the boilers, lying behind a holding bulkhead in a capital ship. In many of the older tests of model protective structures, only the maximum deflections of certain bulkheads were recorded in addition to the photographs showing the deformed shape.

The next step toward a more detailed analysis is to measure the increase in area of the metal in various parts of the structure being tested.

In the tests reported here, in which rupture took place only in exceptional cases, it has been assumed that the increase in the area of the diaphragm was a measure of the progress toward rupture, at least for all cases where backing diaphragms were of the same type, size, and material. Larger increases in area were supposed to bring the structure closer to rupture.

The fourth, and the most refined method known at present, is to determine and utilize the amount of energy absorbed by the structure. Assuming a given quantity of energy in the field of an explosion, and a given quantity delivered to the face of a protective structure, the structure that can absorb or reflect the largest amount of energy, or both, and pass the smallest amount along to the backing bulkhead, is considered to have the greatest merit, all other things being equal.

For the problem in hand, an excellent criterion of the usefulness of a composite structure can be obtained by converting the total weight of the protective assembly, including that of the backing diaphragm, to an equivalent single thickness of steel. This takes account of strict limitations in weight imposed on ship designers, who must provide the maximum degree of protection on a given available weight.

The maximum deflection and the increase in area which occur when this equivalent thickness and weight of steel is subjected to the explosion is then determined by consulting tables such as Tables 1, 2, and 3, or graphs such as Figures 21 and 22, which contain the experimental and derived results of tests made on single-plate steel diaphragms of various thicknesses. If the deflection or the increase in area of the backing diaphragm exhibited by the composite protective structure is less than the deflection or the increase in area observed in the equivalent thickness of steel, the composite structure is considered to have merit. If the deformation is greater than that in an equivalent thickness of steel the construction is regarded as unsuccessful.

To derive a figure of merit, use is made of the ratio of the deflection or the increase in area observed for the equivalent thickness of steel to that observed for the backing diaphragm of the particular protective structure; the former is the numerator and the latter the denominator. Under these circumstances a merit factor of more than 1.0 represents a successful structure, and a merit factor of less than 1.0 an unsuccessful one.

In the same way the energy which was absorbed in producing an observed deformation in the backing diaphragm of a given thickness and material in a composite assembly can be calculated by a simple method (11), later to be described in detail. This energy can then be compared to the energy that would be absorbed by a single steel diaphragm of equivalent thickness when subjected to an attack from a charge of the same size at the same distance.

For example, suppose a backing diaphragm of a composite test assembly is found to absorb 3680 inch-pounds per pound of metal* of the total energy delivered to the assembly by the explosion, and the equivalent single steel plate is found to absorb 4530 inch-pounds per pound of metal when subjected to the same explosive forces. Thus the protective structure has prevented a part of the energy from reaching through to the backing diaphragm. Not only is the gross amount of energy which got through thus reduced, but the reduction is sufficient so that even in the lighter metal of the backing diaphragm the energy absorbed *per pound* has been reduced. This means, in turn, that the protective screen has absorbed or reflected more energy per pound than would the equivalent weight of steel.

The merit factor assigned to the composite structure is $\frac{4530}{3680} = 1.23$. Since this merit factor is greater than 1.0 it indicates that the protective structure with the backing diaphragm is more effective in preventing transmission of damaging energy than an equivalent weight of steel in a single plate.

---

* Kennard (12) recommends that the energy per unit weight of material be used so that the test results will apply to structures of any scale. This is done directly for the merit factor obtained by individual analysis but indirectly for the merit factor obtained by averaging analysis; both are shown in Tables 8 to 19.

All four methods of analyzing damage have been used in this report, but as only a very few diaphragms ruptured or split, even on the second shots, the first method is to all intents and purposes eliminated.

ANALYSIS OF TEST RESULTS BY MAXIMUM DEFLECTION

This is a simple method, and to be effective it should remain simple. No account has therefore been taken of any observed data except the maximum net deflections of the backing diaphragms on the first shots fired against the composite assembly, as compared with the same quantity for a single steel plate of equal weight. These deflection values are set down in the fifth columns of Tables 4, 5, and 6. The merit ratio has then been computed simply by dividing this deflection into the deflection of the single steel-plate diaphragm of equal weight when subjected to the same type, weight, and position of charge.

As the group of reference diaphragms did not include materials of all the equivalent thicknesses listed in Tables 4, 5, and 6, the thickness and deflection data from the upper portions of Tables 1, 2, and 3 were plotted for all Number 1 shots on the reference diaphragms, as shown in Figure 21, and the deflections for the equivalent thicknesses were then picked from smooth curves drawn through the spots.

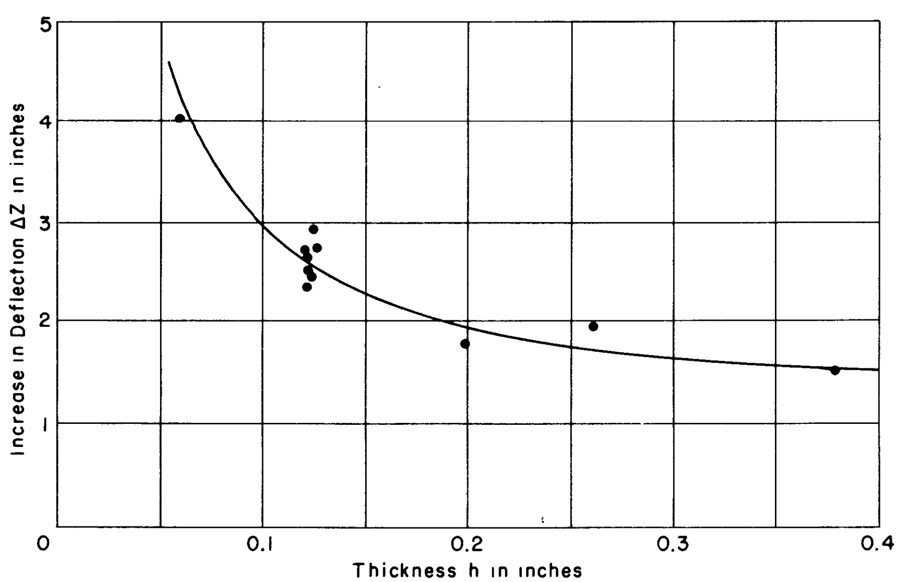


Figure 21 - Typical Plot Showing Relation between Thickness and Maximum Deflection for Reference Diaphragms, Configuration A

Similar curves for the other configurations were plotted from the data of Tables 1, 2, and 3, but these are omitted in this report.

The merit ratios so derived are listed subsequently in Tables 8 to 19 beginning on page 52.

ANALYSIS OF TEST RESULTS BY INCREASE IN AREA

The analysis by increase in area was likewise reduced to its simplest possible form by neglecting all observed data except the increases in area of the backing diaphragms in the composite assemblies.

To obtain the increase in area which the same type, weight, and position of charge would have caused in a single-plate diaphragm of equivalent weight and thickness, six plots were made and smooth curves were drawn on each, to serve as calibration curves for the six configurations mentioned previously on page 28. A representative plot and calibration curve is shown in Figure 22.

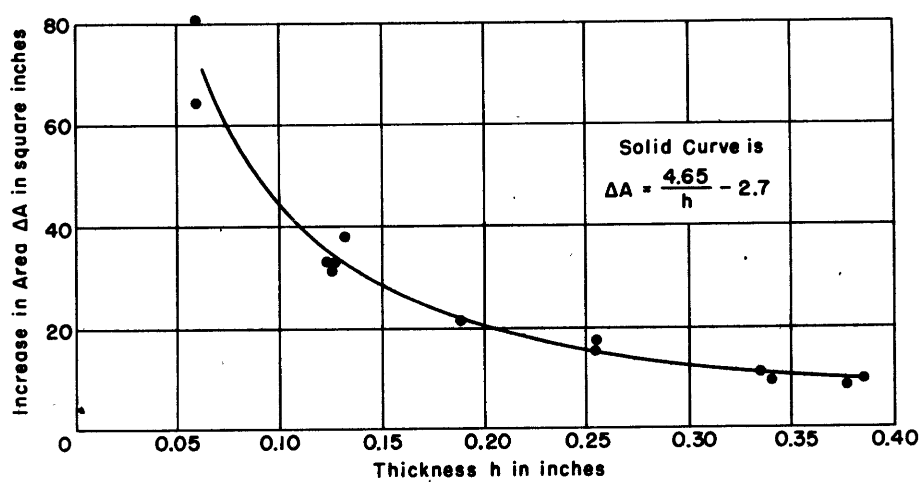


Figure 22 - Typical Plot Showing Relation between Thickness and Increase in Area for Reference Diaphragms, Configuration C

Similar curves were plotted for the other configurations but these are omitted in this report.

On each plot the increase in area was laid down for all the referenced diaphragms in that configuration and a smooth curve was drawn to fit these points.* From the smooth curve a value of ΔA was read off for the equivalent thickness of a given composite assembly. When this was divided by the value of ΔA for the backing diaphragm, a merit factor for that protective structure was obtained.

---

* Actually a hyperbola $\Delta A = \frac{a + b}{h}$ was fitted by sight to the data. The hyperbolic relationship may be roughly justified in terms of nominal theory.

It might be argued that for this analysis, and for the deflection analysis as well, some account should be taken of the uncontrolled and, as it happened, also uncontrollable, variables such as the great variation in yield strength of the steel used. An attempt was made to do this, but it was found that the variations in the behavior of steels of equal yield strengths were in many cases as great as the variations which the analysis was designed to discover. It was apparent that other effects, such as strain-hardening and thinning of the material during deformation, could not be accurately accounted for because of lack of information as to these phenomena in general and their effect on the diaphragms in particular. The attempt to introduce these refinements was therefore deferred until all could be taken in at once, as explained in the following two sections.

Were the entire series of tests to be repeated, with the knowledge and experience now available, much of the work would be done differently. With the precision of measurement actually obtained, and the accidental variations which occurred over the period of this test, the use of a more complete analysis based only upon measurement of the increase in area is considered not justified.

ANALYSIS OF TEST RESULTS BY ENERGY ABSORPTION

As stated previously, a further refinement in estimating the merit of a protective structure is to calculate the percentage of energy in the field which the screen absorbs or reflects and which is prevented from reaching the backing diaphragm. Actually the process is accomplished somewhat in reverse by calculating the amount of energy absorbed by the backing diaphragm of a composite structure, and comparing it with the energy absorbed in the same field by a single-plate diaphragm of equivalent weight and thickness.

The energy absorbed in any case can be computed approximately by a relatively simple method described in TMB Report 490 (11) in which the increase in area of the backing or reference diaphragm is multiplied by its thickness* and then by the value of the plastic stress for the material of the particular diaphragm.

Because the analytical procedure was relatively new and not yet well worked out, this reduction was made by two groups in the Structural Mechanics Division at the Taylor Model Basin who proceeded along independent lines in arriving at a series of merit factors based upon energy considerations. In

---

* The original thickness is used, as it was not possible to determine the instantaneous thickness with apparatus available at the time of the tests, and not practicable to measure the final thickness in the composite assemblies.

both methods it was assumed that the energy absorbed by the diaphragm was not affected by variations in its motion under the action of the charge.

Averaging Analysis

In the first method of analysis, which may be called an averaging method, the total energy absorbed by the backing diaphragm was calculated in the manner just described, using as a value of plastic stress the value of the initial yield stress determined by the customary drop-of-the-beam method and set down in Tables 1, 2, and 3. As explained in Appendix 1, these data were used to derive the equation

$$U_h = U_{0.25}\left[1 - 1.45(h - 0.25)\right] \qquad [1]$$

where U_h is the total energy absorbed by a diaphragm of thickness h, and $U_{0.25}$ is the energy absorbed by an average diaphragm of 1/4-inch thickness.

This method makes use of two energy ratios, R_1 and R_2, the ratio of R_1 to R_2 being taken as the "merit factor" of a given construction. R_1 is the ratio of energy absorbed by an unprotected steel diaphragm of the same thickness as the backing diaphragm, to the energy absorbed by the backing diaphragm when the screen is interposed. R_2 is h_2/h_1 times the ratio of the energy absorbed by an unprotected diaphragm equal in weight to the backing diaphragm to the energy which would be absorbed by an unprotected steel diaphragm of weight equivalent to that of the composite construction.

Individual Analysis

In the second method, the energy absorbed by the backing diaphragm of the composite structure is found as before, except that for first shots the plastic stress used is a mean value found by averaging the stress taken from an actual stress-strain curve, over the range from no strain to a strain equal to the average 2-dimensional strain $\Delta A_1/A$ in the backing diaphragm as a whole. Similarly for second shots the plastic stress is averaged over the strain range from $\Delta A_1/A$ to $(\Delta A_1 + \Delta A_2)/A$. Here A is the original area of the diaphragm and ΔA_1 and ΔA_2 are the changes in area due to Shots 1 and 2, respectively. The average over the range of strain was found not by averaging the end points but by analytical or graphical integration.*

---

* The average plastic stress for Shot 1 is

$$\bar{\sigma}_1 = \frac{1}{\left(\frac{\Delta A_1}{A}\right)} \int_0^{\epsilon_1} \frac{F}{a_0}\, d\epsilon$$

(Continued on next page)

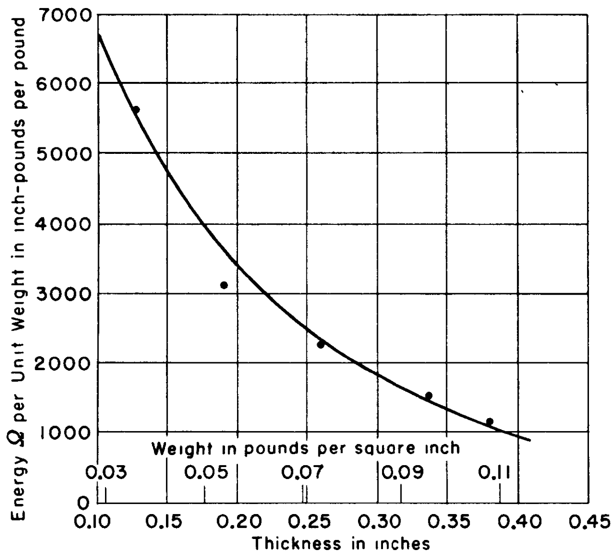


Figure 23 - Typical Plot Showing Relation between Thickness, Weight, and Energy per Unit Weight Absorbed by Reference Diaphragms, Configuration C

The net result of this procedure is to raise slightly the value of the plastic stress used in the energy calculation. A comparison of the various yield strengths for all diaphragms tested has been given previously in the various parts of Table 7 on pages 38 to 42 of the present report. From the data in these tables it is found that the maximum increase is of the order of 34 per cent, but the average increase is only a few per cent.

As explained in the footnote to page 45 the energy absorbed and retained by the diaphragm per unit weight of the diaphragm was used. This quantity, **Ω**, was found by dividing the total energy absorbed by the backing diaphragm by the weight of the backing diaphragm not including the flange.

To find the energy per unit weight which would have been absorbed in a single-plate diaphragm of equivalent weight and thickness, recourse is had to a curve drawn through values obtained for the plain unscreened diaphragms tested in the same configuration, without reference to any tests in other configurations. A sample curve of this kind is shown in Figure 23.

RESULTS OF ANALYSIS

The merit factors derived by these two methods of considering energy absorption are set down in subsequent sections in Tables 8 to 19, beginning on page 52.

When comparing the four merit factors for any given test it must be remembered that as the increase in area and the energy absorption both vary

---

for the second shot

$$\bar{\sigma}_2 = \frac{1}{\left(\frac{\Delta A_2}{A}\right)} \int_{\epsilon_1}^{\epsilon_2} \frac{F}{a_0}\, d\epsilon$$

where $\epsilon_1 = \frac{\Delta A_1}{A}$, $\epsilon_2 = \frac{(\Delta A_1 + \Delta A_2)}{A}$, F is the instantaneous load on the tensile specimen, a_0 is the original area of the tensile specimen, and ϵ is the strain of the tensile specimen.

approximately as the square of the deflection, the merit factor for deflection may be expected to be closer to 1.0 than in any of the other three.

In concluding this portion of the analysis it may again be pointed out that there are many features of this long series of tests, and of this more recent analysis, which will not bear too critical a review.

At the time when the tests were begun at the Taylor Model Basin, facilities for experimental study were almost completely lacking, and had to be developed as the project progressed. Large quantities of sheet- and plate-steel from which groups of diaphragms could be cut were almost impossible to procure, and it was not practicable to plan ahead for a long series of systematic tests without any knowledge whatever as to the trend of the results.

At the time of writing, the several methods of analysis described appear both logical and adequate, and it is doubtful whether, because of the lack of precision in the experimental observations, the expenditure of additional time upon any more elaborate methods is justified.

PERFORMANCE OF FILLING MATERIALS FOR DISSIPATING EXPLOSIVE ENERGY

Inelastic Filling Materials

In References (1), (2), and (3), Bond and Mason concluded that the sharp rise in pressure due to an explosion under water could be highly attenuated by interposing one or more layers of dry sand between the facing and the backing bulkheads of a protective structure.

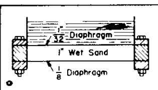
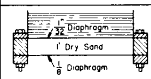
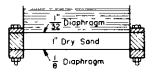
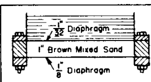
Comparison of the deflections, the increases of area, and the energy values absorbed by the 1/8-inch diaphragms in these tests shows that the sand screening does reduce all these values but that this assembly cannot compare in efficiency with a single plate of steel of equivalent weight.

The results of four tests made with sand fillings are shown in Table 8. In this and in the tables following it will be noted that the four merit factors for each test and shot differ rather widely but that they indicate clearly whether or not the composite construction is better than an equivalent weight of steel.

Although some tests performed by Bond and Mason with small 2-gram pellets of lead azide showed that the detonation wave was considerably reduced in passing through sand and indicated that the transmission of energy from the facing diaphragm to the backing diaphragm is reduced by the presence of sand, it is entirely possible that the explosion wave from the TNT and tetryl charges used in these tests was of longer duration and does not have as steep a front as was anticipated by the original theory in References (1), (2), and (3), and was of longer duration and less steep than the wave produced by the lead azide pellets. If this were the case the attenuation produced by the sand might be considerably less. In other words, it may be that

TABLE 8

Behavior of Attenuating Materials (Sand) in Protective Structures

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
					1-Ounce Charge of TNT at 12 Inches, Configurations A and B						
H-1		1 inch† of wet sand	0.379	1.54	7.0	625	3680	0.66	0.41	0.24	0.17
H-2			0.379		3.6	1225	2770	**	0.28	0.23	0.44
O-1		1 inch of dry sand	0.407	1.51	6.4	450	3110	0.64	0.41	0.25	0.14
O-2			0.407		3.1	1160	2420		0.26	0.24	0.48
Q-1		1 inch of dry sand	0.410	1.51	6.4	440	3040	0.67	0.41	0.26	0.14
Q-2			0.410		3.0	1150	2580		0.24	0.22	0.45
					1/2-Ounce Charge of Tetryl in Contact, Configurations E and F						
BO-1		1 inch of dry brown sand	0.439	1.53	5.1	280	1430	0.89	0.47	0.38	0.20
BO-2			0.439		4.6	600	1250		0.49	0.41	0.48

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick; in all cases the equivalent thickness was computed from accurate weights of the structures. A screened sand, -20 +30 mesh, was used in Tests H and O. In Test Q a 50-50 mixture of this fine screened sand with a commercial grade of "coarse" sand was used. Since there was no apparent difference, common brown sand, unscreened, was used in Test BO.

** Merit factors based on increase in deflection were not calculated for any second shots.

† All the dimensions given in this column in this and similar following tables are only nominal; see the second footnote to Table 4.

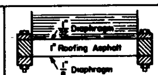
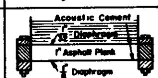
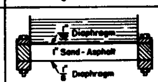
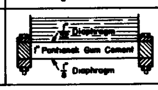
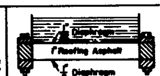
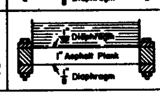
there is not as much high-frequency energy in the Fourier analysis of the explosion pulse as Mason's tests had assumed. Since sand and similar materials would be most effective for the high velocities associated with these high-frequency components such an explanation would account for the poor performance in these constructions.

Following the rather discouraging tests with sand filling, it was proposed that materials such as asphalt might serve to dissipate the energy of the explosion and convert it into heat. Presumably this is accomplished by opposing a frictional force to the motions resulting from the explosive pressure wave. There are analogies here in the damping of automobile body panels by the application of asphaltic coatings.

A number of such materials were tested, such as asphalt, gum cements, and mixtures of these materials. The material which is described as "asphalt plank" is a standard commercial product used for building the floors of bridges. It is a combination of asphalt of fairly high melting point and a stone aggregate. The results of these tests are set forth in Table 9. A view of the asphalt-plank filler in one of the structures is given in Figure 24.

TABLE 9

Behavior of Energy-Dissipative Materials in Protective Structures

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_e of Single Plate inches	Equivalent Deflection ΔZ_e inches	Equivalent Increase in Area ΔA_e square inches	Equivalent Energy in Single Plate Ω_e in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on Energy: Averaging Analysis	Merit Factors Based on Energy: Individual Analysis
1-Ounce Charge of TNT at 12 Inches, Configurations A and B											
N-1		1 inch of roofing asphalt	0.322	1.61	8.6	1050	2820	0.74	0.60	0.41	0.37
N-2			0.322		5.0	1380	2350		0.42	0.35	0.59
V-1		1 inch of asphalt plank	0.351	1.58	7.8	820	2510	0.76	0.54	0.41	0.33
V-2			0.351		4.2	1290	2260		0.33	0.33	0.57
Y-1		1 inch of sand-asphalt emulsion	0.418	1.51	6.2	380	2830**	0.63	0.37	0.27	0.13
Y-2			0.418		2.9	1140	2640**		0.20	0.20	0.43
BA-1		1 inch of Pontianak gum cement	0.310	1.63	9.0	1150	3720**	0.61	0.41	0.32	0.31
BA-2			0.310		5.3	1410	3870**		0.25	0.22	0.36
1/2-Ounce Charge of Tetryl in Contact, Configurations E and F											
BM-1		1 inch of roofing asphalt	0.318	1.70	7.1	970	1580	0.76	0.53	0.60	0.61
BM-2			0.318		6.3	1000	2100		0.36	0.44	0.47
BN-1		1 inch of asphalt plank	0.366	1.62	6.2	650	1950	1.08	0.48	0.43	0.33
BN-2			0.366		5.5	820	2230		0.37	0.36	0.37

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick.
** These values are based on an assumed average yield stress of 51,000 pounds per square inch; see the first footnote to Table 4.

With one rather unimportant exception, Test BN-1, these materials show merit factors much less than 1.0. In all cases the bulging of the backing diaphragm is less than when no protection is provided, but again the weight of the protective materials in this class is such that the constructions are never as good as an equivalent thickness of steel.

Reasoning based on ordinary types of viscous-damping problems is somewhat misleading in the present case. The energies which must be dissipated in an explosion pulse are so tremendous that few materials can even approach the efficacy of steel for this purpose. It is not common to think of steel as a material for dissipating energy in plastic work, but in the case of explosive action this property of the steel is far more important than its elastic properties. In judging dissipative materials, therefore, a more instructive viewpoint is to compare their internal resistance to plastic flow with the internal resistance of the steel fibers themselves.

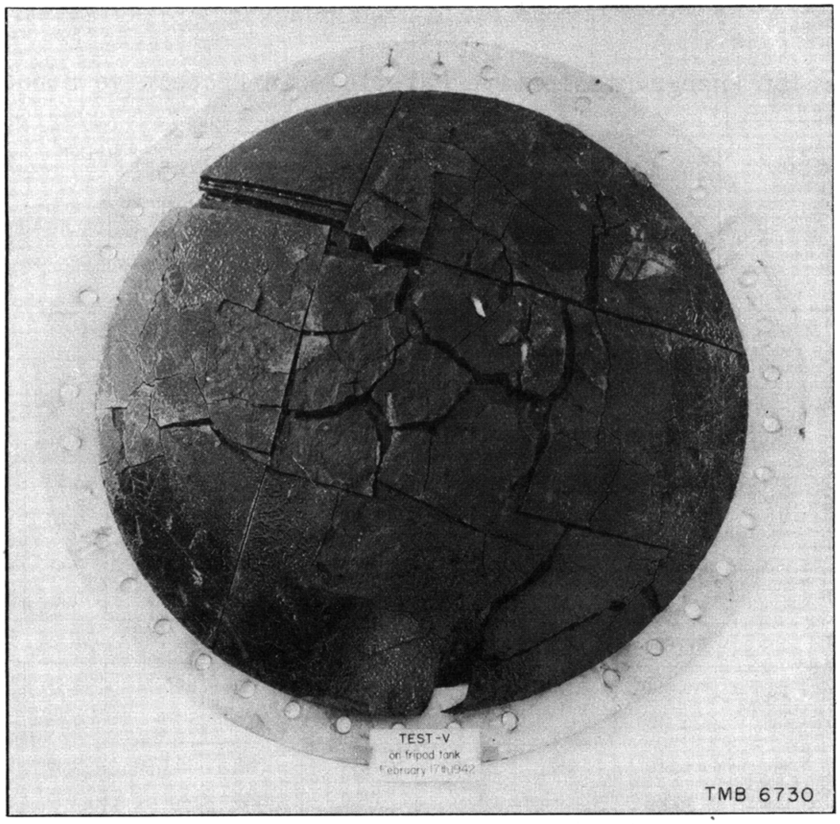


Figure 24 - Illustration of Behavior of 1-Inch Asphalt-Plank Filler

This was from Test V, described in Table 9 on page 53. A 1/32-inch facing diaphragm was on the far side of the asphalt, facing the charge; the rim of this diaphragm shows in the photograph. Two charges of 1 ounce of TNT were fired in succession at a distance of 12 inches.

The merit factor of this assembly was about 0.45.

Elastic Filling Materials

The idea of filling inter-bulkhead spaces with elastic materials has frequently been suggested and several times used in practice.* In terms of the present discussion these elastic materials to be efficient should be capable of storing or dissipating more energy than the equivalent unfilled air space, together with its containing diaphragms. A number of filling materials were tried in these experiments, only one or two of which showed any promise when examined in this light.

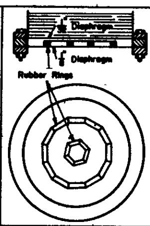
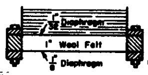
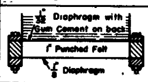
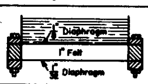
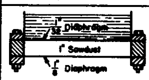
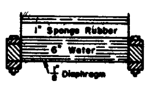
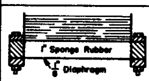
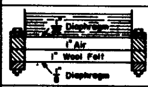
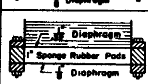
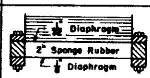
Table 10 lists the tests which are considered to fall in this classification. Several kinds of rubber, two kinds of felt, and sawdust were tried. There may be some question as to whether it is appropriate to include

---

* During the final revision of this manuscript it was learned that, on the French battleship RICHELIEU, the outer layer of voids in the torpedo protection structure was completely filled with a cellular rubber material in the form of bricks. As far as can be learned, the primary purpose of this filling was to plug any tears that might occur in the bulkhead behind it.

TABLE 10

Behavior of Elastic Filling Materials in Protective Structures

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_e of Single Plate inches	Equivalent Deflection ΔZ_e inches	Equivalent Increase in Area ΔA_e square inches	Equivalent Energy in Single Plate Ω_e in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
1-Ounce Charge of TNT at 12 Inches, Configurations A and B											
P-1		Two concentric rubber rings between facing and backing diaphragms	0.158	2.22	19.7	3475	2740	1.01	1.44	1.11	1.27
P-2			0.158		14.3	2600	1610		1.79	1.35	1.61
T-1		1-inch low density wool felt	0.166	2.17	18.7	3300	2400	1.01	1.34	1.19	1.38
T-2			0.166		13.4	2470	2050		1.06	0.93	1.20
BB-1		1-inch punched hair felt	0.206	1.91	14.6	2500	3460**	0.81	0.71	0.58	0.72
BB-2			0.206		10.0	2000	3250**		0.56	0.47	0.62
BD-1†		1-inch felt same as BB reversed	0.208	1.90	14.4	2450	3240	0.69	0.72	0.66	0.76
BG-1		1 inch of dry sawdust	0.168	2.15	18.4	3240	1920	1.05	1.55	1.44	1.69
BG-2			0.168		13.2	2440	2000		1.11	1.01	1.22
1-Ounce Charge of Tetryl at 12 Inches, Configurations C and D											
BT-1+		1 inch of rubber 6 inches above diaphragm	0.154	2.78	27.2	4570	4130	1.00	0.96	0.97	1.11
BT-2+			0.154		22.9	4000	1400		2.39++	2.47++	2.86++
BU-1+		1-inch sponge rubber††	0.152	2.80	27.9	4630	4700	0.93	0.86	0.86	0.99
BU-2+			0.152		23.3	4070	4030		0.87	0.90	1.01
CD-1		1-inch air space over 1-inch wool felt	0.172	2.60	24.3	4070	2580	1.04	1.67	1.39	1.58
CD-2			0.172		20.4	3550	3000		1.28	1.08	1.18
CX-1		1-inch sponge rubber pads††	0.211	2.33	19.3	3150	3450	0.85	0.92	0.82	0.91
CX-2			0.211		16.4	2750	3530		0.85	0.76	0.78
CY-1		2-inch sponge rubber††	0.235	2.21	17.0	2720	2520	0.88	1.08	0.96	1.08
CY-2			0.235		14.6	2400	2500		1.00	0.91	0.96

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick, except in Tests BD, BT, and BU. In Test BD the backing diaphragm was about 1/32 inch thick and the facing diaphragm was about 1/8 inch thick. In Tests BT and BU no facing diaphragms were used.

** These values are based on an assumed average yield stress of 51,000 pounds per square inch; see the first footnote to Table 4.

† All values are for the 1/8-inch facing diaphragm; there are no data for the thin backing diaphragm.

†† The sponge rubber used in Tests BU and CY was a special low-density product with sealed air cells. The pads of Test CX were heavier, low-grade, commercial material.

\+ For Tests BT-1, BT-2, BU-1, and BU-2 the charge was 12 inches above the original position of the backing diaphragm.

++ There is some evidence that there was imperfect detonation on the second shot; therefore the correct values of the merit factors are probably less than those shown.

sawdust in a group such as this; however, the sawdust when packed into the enclosed space possessed considerable resilience. In view of the previous discouraging performance of sand, it was believed that any merit possessed by the sawdust was more likely to be due to its elasticity than to any dissipative effects. It was felt that if there were some elastic action it was more likely to appear when the material is closely packed.

According to the analysis employed, most of the constructions in this category had better merit factors than the equivalent weight of steel. However, if these results are compared with the results for a 1-inch or a 2-inch air space as given in Table 16 on page 76 it will be found that only Tests P, BG, and possibly T were better than the same construction without the filling material.

In Test P the facing diaphragm was bent down and around the separating rubber rings by the force of the explosion. Considerably more work was done on this facing diaphragm as a result of the additional deformation than on other facing diaphragms with more uniform backing behind them. It is considered possible that the apparent excellence of this construction may have resulted from this fact. On the other hand, Test DB,* which was in many respects similar except that the spacing rings were of steel, was not nearly so successful.

It appears possible that when the rubber is heavily loaded, as in Test P, there is some gain in merit factor to be expected. It should be noted that the rubber rings in this case were of fairly hard rubber having a Durometer hardness of about 50. This is in distinct contrast to the softer sponge rubbers used in Tests BU, CX, and CY.

The merit factor for Test BG-1, about 1.5 for a 1-inch layer of sawdust, compares favorably with the merit factor of about 1.4 obtained for Test DG-1, with a 1-inch air space; see Table 16 on page 76.

None of the other constructions appeared sufficiently promising to warrant further tests.

Where different felts or different types of rubber were compared, the protective efficiency decreased as the weight of the filling material increased. With this class of material, increased weight always implies greater stiffness.

EFFECTS OF ADDING INERTIA

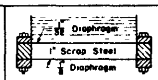
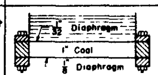
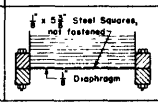
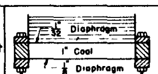
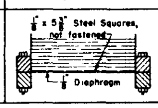
Table 11 gives the results of seven tests in which the principal change introduced was the addition of inertia loading on the backing diaphragm. Actually, however, the desired result was only partly achieved

---

* This is listed at the top of Table 5 on page 35.

TABLE 11

Effect of Adding Inertia to Protective Structures

Test	Composite Structure		Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on			
	Diagram	Description of Filling*						Increase in Deflection	Increase in Area	Energy: Averaging Analysis	Energy: Individual Analysis
1-Ounce Charge of Tetryl at 12 Inches, Configurations C and D											
DA-1		1 inch of scrap steel	0.672	about 1.4**	4.2	less than 10††	3770	0.5**	0.19	0.09	less than 0.01††
DA-2			0.672		4.1	less than 10††	3620		0.21	0.08	less than 0.01††
DC-1†		1 inch of coal	0.292	2.01	13.2	1920	3470	0.73	0.63	0.52	0.55
DC-2			0.292		11.4	1800	3500		0.59	0.48	0.51
ED-1		steel squares laid on diaphragm	0.217	2.30	18.7	3040	5650	0.59	0.45	0.49	0.54
1/2-Ounce Charge of Tetryl in Contact, Configuration E											
DY-1†		1 inch of coal	0.310	1.72	7.3	1020	1270	1.70	1.07	0.78	0.80
EC-1		steel squares laid on diaphragm	0.228	1.92	9.9	1760	3240	0.73	0.47	0.49	0.54

* All backing diaphragms in this group were about 1/8 inch thick. All facing diaphragms were about 1/32 inch thick, except in Tests EC and ED where no facing diaphragms were used.

** The curve to give ΔZ_q was extrapolated beyond the point warranted by the data thus throwing doubt on the corresponding merit factor.

† In Test DC the coal was screened through 1/2-inch mesh and held on 1/4-inch mesh. In Test DY no screening was done.

†† Doubtful extrapolation of the curve actually gave negative values for Ω_q and the corresponding merit factor.

because the masses added were not attached to the backing diaphragm in any way; see Figure 25. However, it is probable that the added masses were constrained to move with the backing diaphragm by the pressure of the facing diaphragm or of the water, so that at least a considerable fraction of their inertia was added to that of the diaphragm.

With one exception, Test DY-1, none of these tests showed a merit factor better than 1.0. The only exception was the test in which a contact charge was fired against a layer of coal; it seems quite possible that the energy absorption here was due to pulverizing of the coal rather than due to any effect of the added inertia.

In Test DA short lengths of steel rod were placed at random between the usual 1/32-inch facing diaphragm and 1/8-inch backing diaphragm. These lengths of rod filled the 1-inch space between the diaphragms, as shown in Figure 25. This scrap steel greatly added to the weight of the construction and there was a corresponding reduction in the merit factor, although the bulging of the backing diaphragm was considerably reduced.

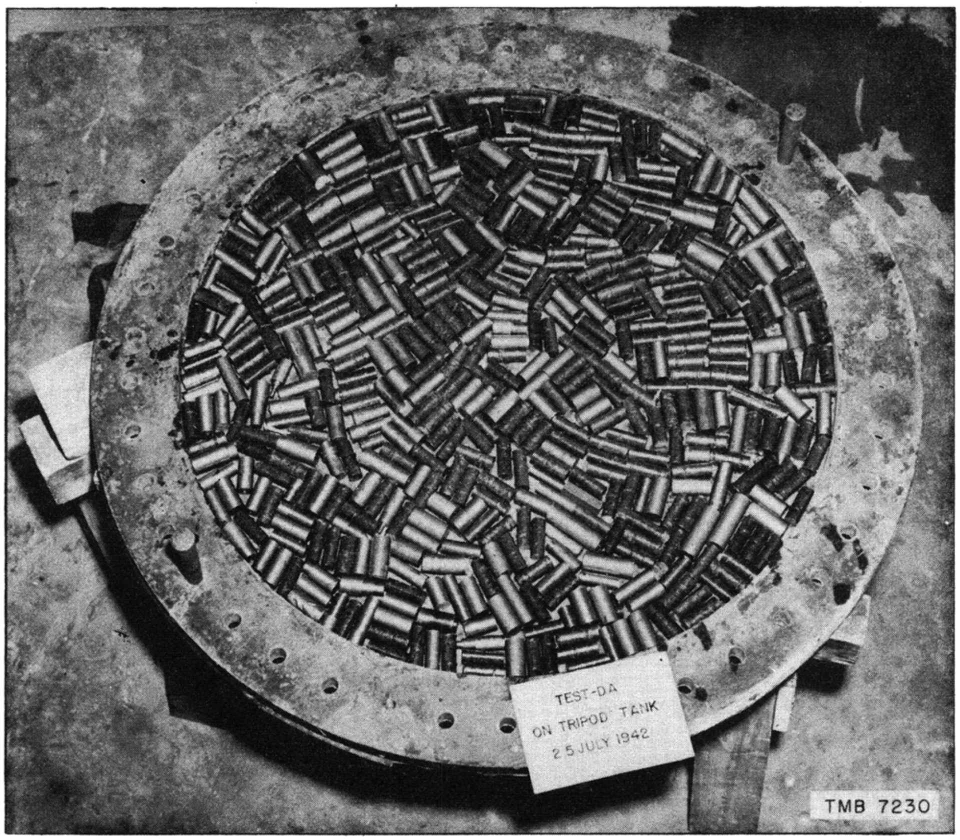


Figure 25 - Arrangement of Loose Scrap-Steel Filling between Diaphragms

Although it was not appreciated at the time, the fact that the pieces of scrap were not firmly attached to the backing diaphragm, shown under the rods in this photograph, rendered this test not a true measure of the effect of inertia loading on the backing diaphragm.

When coal was substituted for the steel scrap the results were considerably better, but still not good enough to justify the added weight. These tests indicate that there would be no object in using coal in this manner unless it were necessary to carry the coal anyway.

Since Tests DA and DC were slightly confused by the fact that a partially filled air space was present, a different experiment was devised in which pieces of 1/8-inch sheet steel were cut into 5-inch squares and laid directly on the 1/8-inch backing diaphragm which formed the bottom of the tank. No other protection was employed in this test. Comparison of the results of Test ED-1 with a test on a similar unprotected 1/8-inch diaphragm shows that the deflection for ED-1 was actually greater than for the unprotected diaphragm. In other words, the added inertia not only provided no advantage but, on the first shot at least, made matters worse.

These inertia constructions are of particular interest in connection with the mechanical filter theory. Presumably, by adding mass without any corresponding increase in stiffness, the "swing time"* of the system was lowered. Since the duration of the pressure pulse is already only a small fraction (1/10th or less) of the swing time of the 36-inch diaphragms used, any further increase in the swing time produced by an increase in mass should reduce the observed deflections by a factor proportional to the square root of the mass ratio. Test DA, for example, does show a smaller deflection and a smaller increase in area than the average for 1/8-inch reference diaphragms. However, Tests ES and ED show greater deformations than the simple reference diaphragm. Since it is possible that the residual air space left in Test DA could account for the improvement shown, an attempt to apply mechanical filter theory experimentally appears to yield definitely negative results.

DISSIPATION OF ENERGY BY FLUID FRICTION

At the suggestion of several investigators various methods of applying the principle of fluid friction were tested during the course of this project. Since the results of these experiments were not particularly promising, this line of attack was soon abandoned. However, three of the tests in which the fluid friction principle was employed are listed in Table 12, in conjunction with control tests suitable for comparison.

The construction designed to utilize the friction of fluids to dissipate energy was a perforated disk of steel, covered with a sheet of waxed paper on the side facing the water, to keep it watertight until the explosion pulse arrived. In Test CH, listed in Table 12, the paper-covered perforated plate was used as an intermediate bulkhead with liquid loading below the facing diaphragm; in Tests CI and CR it was exposed directly to the water in the tank.

In each of the fluid-friction tests the waxed paper over most of the perforations was ruptured by the explosion. The amount of energy absorbed by the tearing of the paper and the forcing of the water through the holes is a measure of the efficacy of the design.

It was hoped that the energy required to force the water through the small perforations might be sufficient to reduce materially the residual energy which had to be absorbed by the backing diaphragm. Comparison of Tests CH and CG, which were identical except that for the latter test the intermediate diaphragm was unperforated, shows that the perforated construction did, in fact, provide a slightly better protection. However, comparison with Test CJ, where a simple 2-inch air space with no intermediate diaphragm was used, indicates that this construction gave a considerably better merit factor.

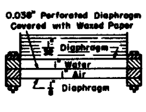
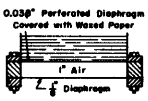
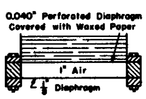
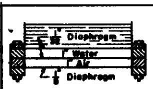
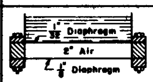
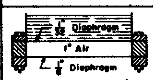
---

* This is defined as the time taken for a flexing structure to reach its value of maximum deflection, reckoned from the start of the motion; see Reference (13) and Appendix 4.

TABLE 12

Behavior of Fluid-Friction Constructions and Reference Constructions

A charge of 1 ounce of tetryl was exploded on the axis 12 inches distant, Configuration C.

Test	Composite Structure: Diagram	Composite Structure: Description of Layers from Dry Side up	Equivalent Thickness h_e of Single Plate inches	Equivalent Deflection ΔZ_e inches	Equivalent Increase in Area ΔA_e square inches	Equivalent Energy in Single Plate Ω_e in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
CH-1		1/8-inch diaphragm, 1-inch air space, 0.038-inch perforated* diaphragm covered with waxed paper, 1-inch water, 1/32-inch diaphragm	0.180** 0.284	2.54** 2.04	23.0** 13.6	3850** 2000	1660	1.16** 0.93	2.30** 1.36	2.02** 1.12	2.32** 1.20
CI-1		1/8-inch diaphragm, 1-inch air space, 0.038-inch perforated* diaphragm covered with waxed paper	0.151	2.80	28.0	4690	4100	0.99	1.17	1.07	1.14
CR-1		1/8-inch diaphragm, 1-inch air space, 0.040-inch perforated* diaphragm covered with waxed paper	0.158	2.74	26.7	4450	3740	1.24	1.18	1.06	1.19
Control Tests											
CG-1†		1/8-inch diaphragm, 1-inch air space, 1/32-inch diaphragm 1-inch water, 1/32-inch diaphragm	0.178** 0.306	2.55** 1.98	23.3** 12.5	3950** 1750	2320	0.98** 0.76	1.69** 0.91	1.49** 0.72	1.70** 0.75
CJ-1		1/8-inch diaphragm, 2-inch air space, 1/32-inch diaphragm	0.149	2.83	28.5	4740	2670	1.05	1.89	1.64	1.78
DG-1		1/8-inch diaphragm, 1-inch air space, 1/32-inch diaphragm	0.163	2.70	25.8	4300	2530	0.90	1.16	1.51	1.70

* In Tests CH and CI the perforated diaphragms had 1/8-inch holes on 1/4-inch centers. In Test CR the perforated diaphragm had 1/16-inch holes on 3/8-inch centers.

** These values were computed by omitting the weight of water in the diaphragm structure. The water may be replaced by oil fuel on a ship. In the unstarred values for Tests CH and CG the weight of the water was included, and low merit factors resulted.

† The results for Test CG-2 are shown in Table 18.

The liquid loading added considerably to the weight of the construction and hence reduced the merit factor. It appears that there is some advantage from the perforated construction, but only if there is need to carry the liquid for some other purpose.

Tests CI and CR, which differ only in the size and number of the perforations used, may properly be compared with Test DG in which, instead of a perforated facing diaphragm, a continuous diaphragm was used. In these cases there appears to have been no advantage from the perforated construction, either in terms of the protection or in terms of the merit factor.

PERFORMANCE OF COMPOSITE STRUCTURES WITH WOOD

General

As explained at the beginning of this report, it was felt that an investigation of the usefulness of wood as an explosive screen in a composite structure could well be included as a part of the series of experiments under discussion.

The test constructions were made up in two forms: Those in which the wood was used solely as a filler between the facing and the backing diaphragms, and those in which it was clamped at the edge to form a sort of structural layer. A thin facing diaphragm about 1/32 inch thick was used in all the assemblies; this was in direct contact with the wood. The wood filling was in turn supported by the usual nominally 1/8-inch backing diaphragm. In one or two cases the assembly was cemented together but there appeared to be no advantage to this procedure and the cement was accordingly eliminated.

Wood Fillers without Edge Constraints

In all the earlier experiments, in which the wood was merely laid between the two diaphragms and was not constrained at the edges by the clamping ring, the inertia or the damping effect of the wood may have been important, but the stiffness was greatly reduced by the absence of edge clamping.

Figures 26 to 30 inclusive show parts of typical assemblies after test, and Table 13 on page 67 contains the results of the first series of wood tests.

There are a number of suggestive comparisons. The only difference between Test R and Test S lies in the fact that the plywood in Test S had been soaked overnight in water. There was a slight improvement in the actual protection but the additional weight reduced the merit factor.

The effect of increasing the thickness of the wood may be seen by comparing Test CS with Test R, or Tests BL, BW, BZ, with CA. The results are contradictory but there is some evidence of improvement with increasing thickness.

In Tests CK and CL, blocks and disks, respectively, were substituted for a single filler piece. The fact that these changes reduced the effectiveness of the construction makes it appear that flexural stiffness or rigidity is an essential factor.

Table 13 also permits a comparison of the effectiveness of the wood for contact charges and for non-contact charges. For this purpose Tests R and CS may usefully be compared with Tests BL and BW, respectively. It appears that the plywood in these cases is somewhat more effective for a contact charge.

(Text continued on page 68)

Figure 26 - Facing Diaphragm of Wood-Filled Assembly after Explosion

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test CL. This is the water side of a 1/32-inch diaphragm laid over four disks of 1/2-inch plywood acting as fillers on top of the backing diaphragm. Two charges of 1 ounce of tetryl were fired in succession at 12 inches.

The merit factor of this assembly was about 0.65.

Figure 27 - Plywood Filler, Water Side, after Explosion

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test BL. This is the water side of the 1-inch plywood filler, to which the facing diaphragm of 1/32-inch steel was attached with Pontianak gum cement. Two charges of 1/2 ounce of tetryl were fired in succession in contact with the facing diaphragm.

Figure 28 - Plywood Filler, Air Side, after Explosion

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test BL. This is the air side of the 1-inch plywood filler, to which the backing diaphragm of 1/8-inch steel was attached with Pontianak gum cement. Two charges of 1/2 ounce of tetryl were fired in succession in contact with the facing diaphragm.

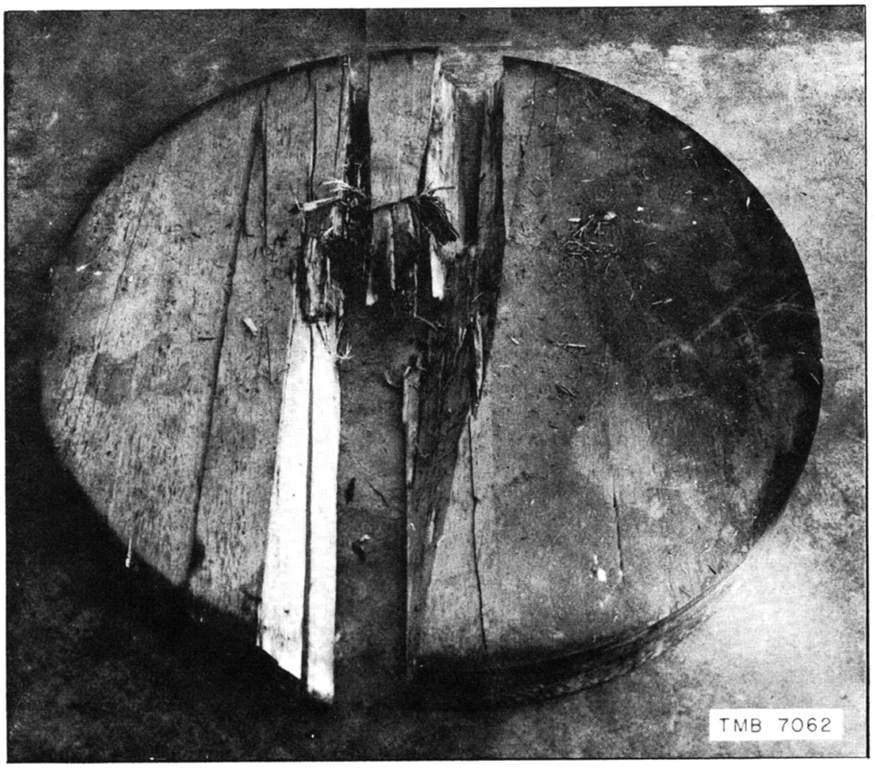


Figure 29 - 3 1/2-Inch Wood Filler after Explosion

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test CA. This is the water side of the assembly after removal of the 1/32-inch steel facing diaphragm. Three charges of 1/2 ounce of tetryl were fired in succession in contact with the facing diaphragm.

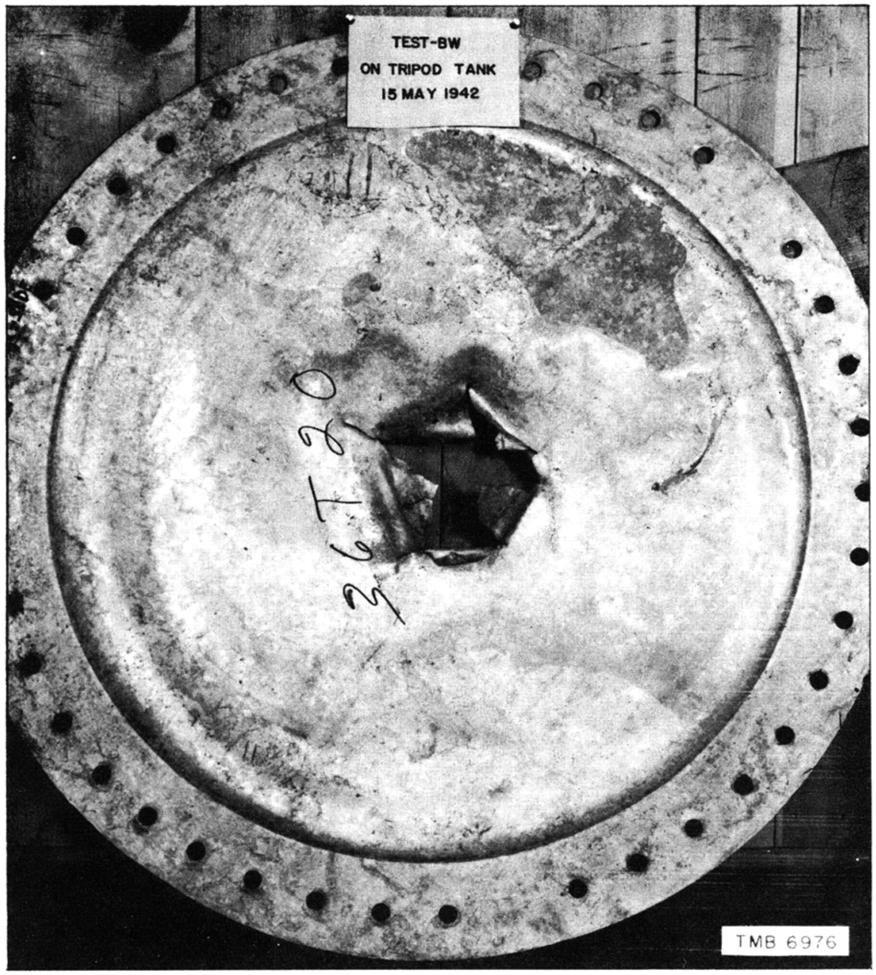
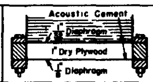
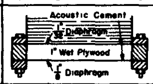
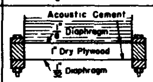
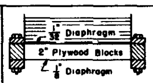
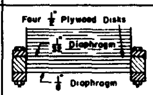
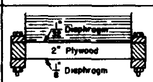
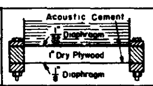
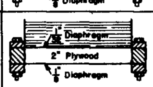
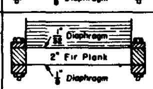
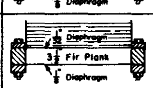


Figure 30 - Facing Diaphragm of Wood-Filled Assembly after Explosion

The structure of this assembly is shown schematically in Table 13, page 67, opposite Test BW. This is the 1/32-inch facing diaphragm, looking from the filler side toward the water. Note the dishing of the diaphragm all around due to compression of the filler under more or less uniform water pressure, and the rupture of the diaphragm toward the charge. Three charges of 1/2 ounce of tetryl were fired in succession; the first in contact with this diaphragm, and the last two in contact with the filler.

TABLE 13

Behavior of Composite Assemblies with Wood Protection Unclamped at Rim

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
1-Ounce Charge of TNT at 12 Inches, Configurations A and B											
R-1 R-2		1-inch plywood disk 34 1/2 inches in diameter	0.236 0.236	1.80	12.5 8.2	2000 1750	2760 2860	0.90	1.04 0.67	0.65 0.45	0.72 0.61
S-1 S-2		1-inch plywood disk 34 1/2 inches in diameter soaked in water	0.243 0.243	1.78	12.1 7.9	1900 1710	2670 2780	0.84	0.91 0.58	0.65 0.46	0.71 0.62
BC-1†		1-inch plywood disk 34 1/2 inches in diameter	0.263	1.72	11.0	1630 1630	1170 2490	0.77 0.80	0.76 0.73	** 0.64	1.39 0.65
1-Ounce Charge of Tetryl at 12 Inches, Configurations C and D											
CK-1 CK-2		plywood blocks 2 inches thick and 5 3/4 inches square	0.288 0.288	2.03	13.4 11.2	1960 1830	4030 4250	0.74	0.59 0.51	0.48 0.42	0.49 0.43
CL-1 CL-2		four 1/2-inch plywood disks 34 1/2 inches in diameter not glued	0.307 0.307	1.98	12.4 10.5	1750 1680	2820 2290	0.86	0.72 0.81	0.61 0.70	0.62 0.73
CS-1 CS-2		2-inch plywood disk 34 1/2 inches in diameter	0.307 0.307	1.98	12.4 10.5	1750 1680	2230 1905	0.91	0.86 0.89	0.73 0.77	0.78 0.88
1/2-Ounce Charge of Tetryl in Contact, Configurations E and F											
BL-1 BL-2		1-inch plywood disk 34 1/2 inches in diameter	0.236 0.236	1.90	9.5 8.5	1680 1480	960 1180	1.12	1.18 0.85	1.51 1.17	1.75 1.25
BW-1 BW-2		2-inch plywood disk 34 1/2 inches in diameter	0.301 0.301	1.73	7.5 6.8	1100 1080	1180 1380	1.47	0.93 0.72	0.88 0.71	0.93 0.78
BZ-1 BZ-2		2-inch fir plank,†† 34 1/2 inches in diameter	0.283 0.283	1.77	7.9 7.1	1240 1180	352 1070	1.81	3.31 0.97	3.21 0.99	3.52 1.10
CA-1 CA-2		3 1/2-inch fir plank,†† 34 1/2 inches in diameter	0.368 0.368	1.62	6.1 5.4	640 810	746 670	2.79	1.30 1.29	1.02 1.08	0.86 1.21

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick, except those in Test BC in which the backing diaphragm was about 1/32 inch thick and the facing diaphragm was about 1/8 inch thick.

** Averaging analysis is not applicable to diaphragms less than 1/8 inch thick.

† Where double values are shown in this row, the upper one is based on the thin backing diaphragm and the lower one is based on the inner 1/8-inch diaphragm.

†† In Test BZ the filling was made up of 2-inch planks of various widths laid in place. In Test CA the filling was made up of 4 by 4's glued together to form a solid plank, then dressed down to a thickness of 3 1/2 inches.

In this connection it may be of interest to refer again to the photographs of the typical plywood disks in Figures 16, 17, 18, and 19, on pages 23, 24, 25, and 26, respectively, which were taken after contact explosions. The surface of the wood has been torn out to a considerable depth and the fibers have been shredded into small bundles. There is evidence of much more work here than in a simple bending or compression failure. However, any attempt to explain this phenomenon at the present state of knowledge would be entirely conjectural. It has been suggested that the shredding action is the result of pressure built up by the explosion wave in moisture which has penetrated the pores of the wood.

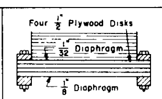
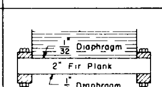
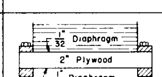
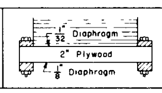
The most significant fact to be observed from these tests is that wood is the first material yet investigated to show an effectiveness even approaching that of steel.

Wood Structural Members with Clamped Edges

In the second group of tests with wood assemblies, in which the wood was to act as a structural layer, the most obvious way of increasing the flexural stiffness of the wood was to clamp the edges of the material by the same clamping ring used for the steel diaphragms. Several tests in which the wood was so arranged are reported in Table 14, and a photograph of one of the wood layers is shown in Figure 31.

TABLE 14

Behavior of Composite Assemblies with Wood Disks Clamped at Edges

Test	Composite Structure		Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on			
	Diagram	Description of Filling*						Increase in Deflection	Increase in Area	Energy: Averaging Analysis	Energy: Individual Analysis
1/2-Ounce Charge of Tetryl in Contact, Configurations E and F											
CM-1		four 1/2-inch plywood disks, not glued	0.307	1.72	7.3	1050	516	1.55	2.29	1.94	2.03
CM-2			0.307		6.5	1050	1410		0.76	0.68	0.74
CO-1		2-inch fir plank, tongued and grooved, glued	0.251	1.86	9.0	1520	576	1.62	2.80	2.37	2.64
CO-2			0.251		8.0	1370	1670		0.86	0.78	0.82
CP-1		2-inch plywood disk	0.306	1.73	7.3	1050	370	1.94	3.50	2.75	2.84
CP-2			0.306		6.6	1060	1270		0.91	0.76	0.83
1-Ounce Charge of Tetryl at 12 Inches, Configuration C											
DD-1		2-inch plywood disk	0.299	2.00	12.8	1840	1820	1.22	1.17	0.96	1.01

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick.

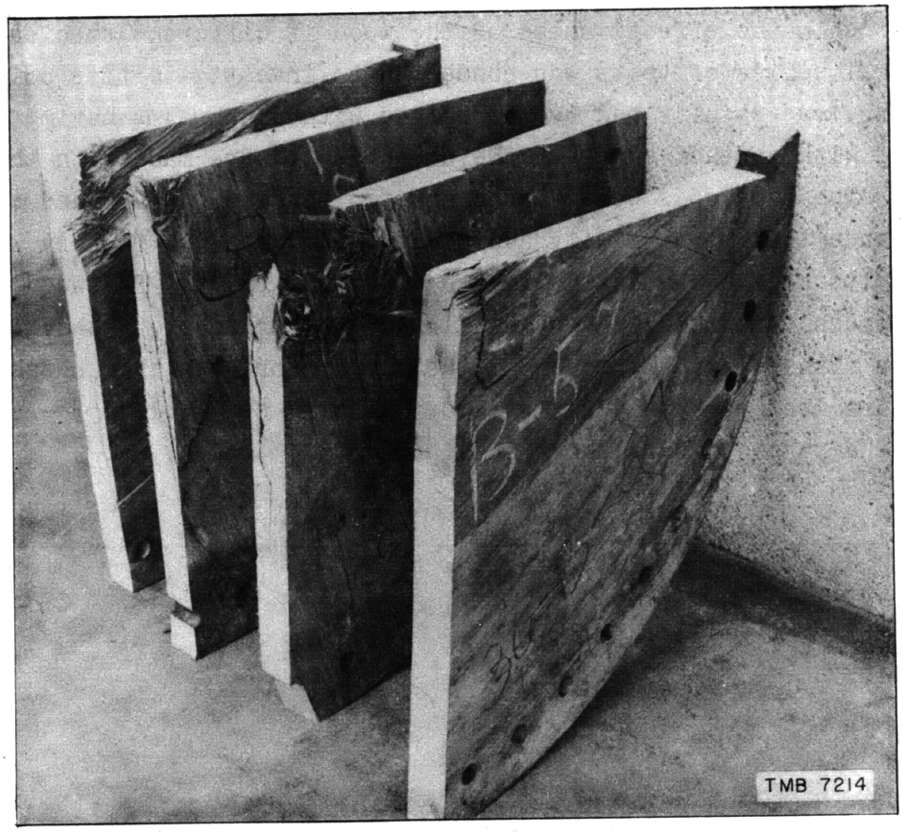


Figure 31 - Wood Structural Layer after Explosion

The structure of this assembly is shown schematically in Table 14, page 68, opposite Test CO. The wood was 2 inches thick, faced with a 1/32-inch steel diaphragm, backed with a 1/8-inch diaphragm, and attacked by two 1/2-ounce charges of tetryl fired in succession in contact with the facing diaphragm. The merit factor of this construction was about 2.5.

Tests CM and CP in which contact shots were fired, show distinct improvement for the clamped-wood construction. The much lower merit factor on the second shot here, as elsewhere, is explained by the fact that the wood was severely damaged on the first shot. The improvement due to clamping is not nearly so marked for Test DD, but in general it is quite clear that increased edge constraint is desirable. Test CO shows no improvement over Test BZ which may indicate that the 2-inch planks possessed more inherent flexural stiffness than the plywood in the unclamped condition.

Effect of Variation in Wood Species

The tests up to this point used readily available materials such as commercial plywood* and Douglas fir plank. Since it appeared that there would

---

* The plywood used was in all cases 5-ply 1/2-inch material with a facing of Douglas fir veneer and a gumwood core. Where greater thicknesses were desired they were built up from layers of this 1/2-inch stock glued together.

be variations in the effectiveness of the wood if different species were used an additional series of tests was conducted to investigate this point. As the best previous results had been obtained with diaphragms having edge constraint and with contact charges, the comparisons were made with this construction. Two hardwoods were tested and two softwoods. Fir and oak were chosen because they were readily available commercially. Hickory was tried because of its high mechanical strength in static tests. Basswood was investigated because this wood is very difficult to tear apart, although its strength is rather low. Considering the values for both thicknesses the wood which appears most generally satisfactory is oak; see Table 15. A photograph of one of the oak layers is shown in Figure 32.

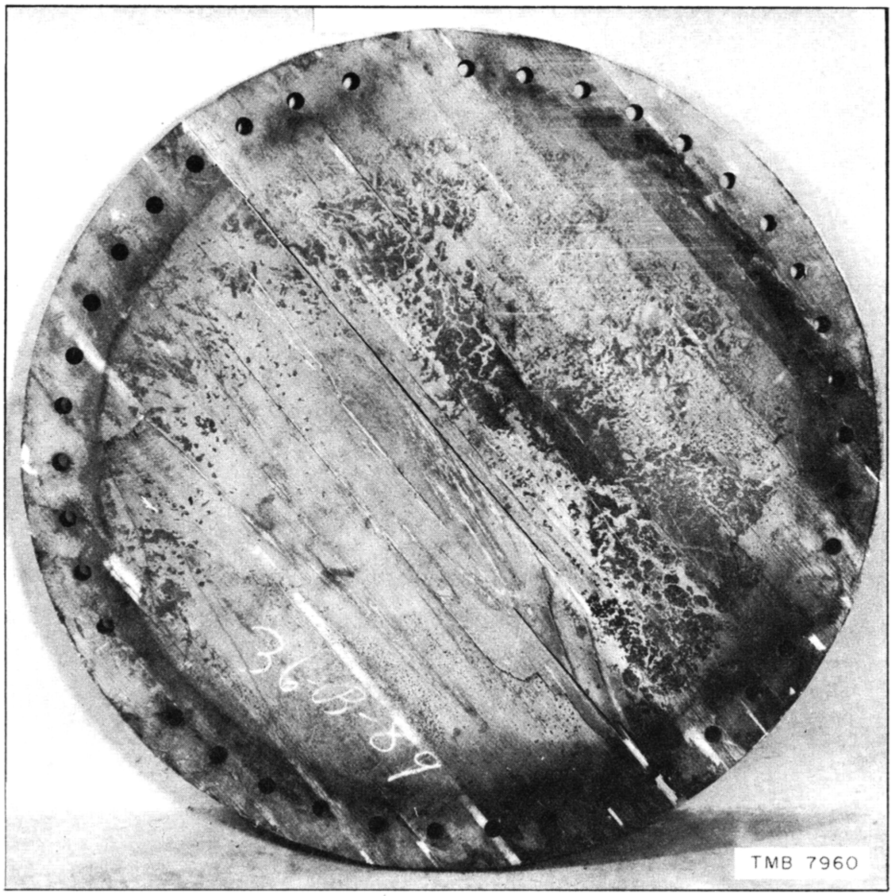


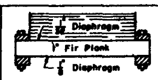
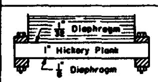
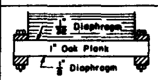
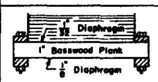
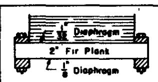
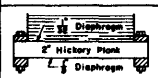
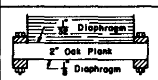
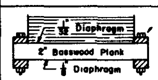
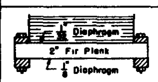
Figure 32 - 2-Inch Oak Layer in Composite Structure after Explosion

The structure of this assembly is shown schematically in Table 15, page 71, opposite Test DU. This layer was made of 2-inch oak strips glued together, and was attacked by a 1-ounce charge of tetryl in contact with the facing diaphragm on the opposite side.

The merit factor of this construction was about 2.0.

TABLE 15

Effect of Variations in Wood Species when used in Clamped-Edge Assemblies

Test	Composite Structure: Diagram	Composite Structure: Description of Filling*	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy: Averaging Analysis	Merit Factors Based on: Energy: Individual Analysis
					1/2-Ounce Charge of Tetryl in Contact, Configuration E						
DO-1		1-inch fir plank	0.225	1.93	10.0	1800	1430	0.91	0.80	1.12	1.26
DP-1		1-inch hickory plank	0.257	1.83	8.8	1480	608	1.05	1.56	2.16	2.43
DQ-1		1-inch oak plank	0.258	1.83	8.7	1470	594	1.10	1.75	2.21	2.47
DR-1		1-inch basswood plank	0.218	1.96	10.3	1870	1020	0.86	1.20	1.60	1.83
					1-Ounce Charge of Tetryl in Contact++						
DS-1		2-inch fir plank	0.286	3.31**	25.3†	3500††	2190	1.53	1.76	+	1.60
DT-1		2-inch hickory plank	0.357	2.65**	20.2†	2800††	1880	1.36	2.17	+	1.49
DU-1		2-inch oak plank	0.363	2.61**	19.9†	2760††	1830	1.47	2.21	+	1.51
DV-1		2-inch basswood plank	0.265	3.58**	27.3†	3780††	3450	1.50	2.84	+	1.10
EA-1		2-inch fir plank	0.299	3.18**	24.2†	3350††	1750	1.62	2.75	+	1.91
DJ-1		single plate	0.260 actual	3.64 actual	27.8 actual		3850				

* All backing diaphragms in this group were about 1/8 inch thick and all facing diaphragms were about 1/32 inch thick. All disks were made from planks, tongued and grooved, glued together, and clamped at the edges.

** These values were calculated by assuming $\Delta Z_q = k_1/h$ and determining k_1 from Control Test DJ-1.

† These values were calculated by assuming $\Delta A_q = k_2/h$ and determining k_2 from Control Test DJ-1.

†† These values were calculated by assuming $\Omega_q = k_3/h$ and determining k_3 from Control Test DJ-1.

\+ These configurations are not covered in the averaging analysis.

++ This is not one of the six standard configurations.

In general the hardwoods were more effective than the softwoods, although the test with a 2-inch basswood plank showed unexpectedly good results. Tests CP and CO listed in Table 14 may also be compared to show the effect of the kind of wood used. Test CP, in which plywood was fitted appears to be slightly better than similar construction in which fir plank was used. This is of special interest, as it has frequently been suggested that plywood, in which the grains of the various layers are customarily placed at right angles to each other, should for this reason be a better material for this purpose. The comparison of these two test results bears this out.

The 2-inch wood constructions were tested with a full 1-ounce charge in contact instead of the customary 1/2 ounce, to get a greater amount of damage and to facilitate comparison.

A special control test, DJ, was made for this purpose, in which a 1-ounce charge of tetryl was fired in contact with a 1/4-inch unprotected steel diaphragm. This test has been included in Table 15 for comparison.

The merit factors for Tests DS, DT, DU, and DV have been evaluated by assuming that ΔZ_q, ΔA_q, and Ω_q each vary inversely as the thickness and by determining the constants of proportionality from the results of Test DJ. The resulting curves are similar to the calibration curves corresponding to Figures 21, 22, and 23 on pages 46, 47, and 50, respectively, for 1/2-ounce contact shots of tetryl. This is a somewhat arbitrary procedure, but it is considered justifiable as the primary point of interest is the comparison of the performance of wood of different species.

The strength properties of wood used for these tests were not measured and these properties vary a great deal with the water content and other uncontrolled conditions in the wood. Therefore, it is likely that the results of these single tests may differ considerably from the averages that would result if many tests were performed on the same structures.

General Comment on Wood Sheathing

It is apparent from the foregoing that, if adequately restrained at the boundary, wood sheathing over a steel backing plate may give better protection against contact charges on the scale tested than is attainable with a single thickness of steel of equal weight.

Several possible explanations of this phenomenon may be suggested. Using statical considerations first, it is to be noted that the elastic deflection of a clamped diaphragm for small deflections is inversely proportional to Eh^3, where h is the thickness. If two diaphragms, one of steel and one of wood, have equal weight, the steel diaphragm will have about 1/12 the thickness of the wood. The ratio of E for steel to wood is about 15 to 1. Hence the wood diaphragm will be much stiffer for *small deflections*. However, for large deflections the diaphragm will act like a membrane and the deflection will be inversely proportional to $\sqrt[3]{Eh}$. In this case the steel plate will show a somewhat greater stiffness. Furthermore, the wood will reach its failure point much sooner, and for deflections of more than 2 or 3 inches in the assemblies under consideration, will probably offer very little restoring force. It appears quite possible that the greatly increased amount of work necessary to overcome the initial stiffness of the wood diaphragm, as compared to the work done for small deflections of the steel diaphragm, may explain the effectiveness of the wood.

Considering the matter from the dynamical standpoint, it also appears possible that the wood may oppose rapid changes in shape with a considerable force due to internal friction, even for deflections beyond the point of initial failure. The shredding, which may be seen in Figures 29 to 31, is not typical of statical failures. A considerable amount of energy may have been absorbed in this destruction of the fibers. Again, however, the phenomenon is confined to small deflections; for large deflections complete failure occurs.

In order to investigate the matter further two assemblies were tested under static load.

Two composite diaphragms were made up, and were loaded to failure under static conditions. The free diameter of these models was 20 inches, instead of 36 inches as in the specimens loaded by explosion.

The first of these assemblies consisted of two disks of furniture steel 0.026 inch thick, separated by 1/2 inch of wood consisting of 3 plies, cross-grained and glued together, but not secured to the steel. The edges of the wood filler were clamped between the edges of the steel disks. The weight of the whole, wood and steel, was 3.58 pounds per square foot.

The pressure-deflection curve of this combination was fairly linear, and the central deflection attained a value of 3 inches at a pressure of 350 pounds per square inch.

Regarding the whole assembly as a unit, the effective stress resisting the plastic flow may be estimated from the formula*

$$P = 4\sigma \frac{h}{a} \frac{Z}{a}, \text{ assuming } Z \ll a$$

where P is the pressure, 350 pounds per square inch,

σ is the effective plastic stress in pounds per square inch,

a is the radius of the disk, 10 inches,

h is the thickness, 0.552 inch, and

Z is the central deflection, 3 inches.

Substituting for the effective plastic stress, σ is found to be 5300 pounds per square inch.

---

* This is Equation [16] of TMB Report 492, Reference (14).

The energy absorbed in the process of plastic deformation is given by Equation [18] of TMB Report 492 (14), and is

$$U = \pi \sigma h Z^2$$

With the numerical values given, this is

$$U_W = 82{,}800 \text{ inch-pounds}$$

For comparison with this it is calculated that a diaphragm of equal weight but consisting of a single sheet of steel of thickness 0.088 inch, loaded to a plastic stress of 40,000 pounds per square inch, would absorb an amount of energy

$$U_S = 11{,}060\ z^2 = 99{,}500 \text{ inch-pounds}$$

For equal deflections of 3 inches, therefore, the diaphragm with the plywood insert absorbed less energy than could be expected from a solid steel disk of the same weight under similar static conditions.

Data are not available to indicate which diaphragm would go to the greater deflection prior to rupture, but it may be concluded that under static load no benefit for energy absorption is to be expected from wood backing for relative deflections equal to or greater than 3 inches in these assemblies.

A second similar test was made with oak flooring in place of plywood; this was tongued, grooved, and glued, 1 inch thick, and, like the plywood, was faced with furniture steel. The weight per square foot was 4.12 pounds. At a pressure of 425 pounds per square inch the deflection was 2.87 inches. The effective plastic stress was 3500 pounds per square inch and the energy, at the deflection noted, was 95,000 inch-pounds. At the same deflection an equal weight of steel would absorb 105,000 inch-pounds, a result similar to that obtained with plywood.

The superiority of steel sheathed with wood over an equivalent weight of steel in a single plate, as found in the tests under explosive load, is thus not found under static load at these deflections. There was, however, some evidence from the load-deflection curve for oak that for deflections up to 3/4 inch the oak was superior to an equivalent weight of steel. As previously noted, there are theoretical considerations which indicate that wood should be superior for small deflections. However, it was not possible to obtain accurate pressure-deflection data for small deflections because the wood was never tightly in contact with the retaining steel diaphragm. The first increments of pressure closed up the interspaces without producing a true deflection in the outer steel diaphragm.

Dynamical considerations, such as the effect of internal resistance on rapid motions, do not, of course, apply to the conclusions drawn from the static tests reported. Since the tests under explosive pressure show an advantage for the wood even for relatively large deflections up to 2 or 3 inches, it is evidently necessary to look to dynamical considerations for the explanation.

MULTIPLE-DIAPHRAGM CONSTRUCTIONS WITH AIR SPACES

A set of composite structures was also made up, in which the material was divided between two or three diaphragms separated by air spaces. In substance this is the system in actual use on ships, as shown in Figures 1 and 2, and its test on small scale was intended to serve as a check on the small-scale work, since the only large-scale data available were for systems built on this principle.

Nine different types of assemblies were made up. All used approximately the same total thickness of steel, between 1/8 inch and 5/32 inch. Five of these assemblies had 1/32-inch facing and 1/8-inch backing bulkheads, with air spaces varying in thickness from 1 inch to 3 inches; the structural details are shown schematically in the upper part of Table 16. The other four assemblies had various dispositions of facing and backing bulkheads and air spaces; details are shown in the lower part of Table 16.

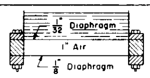
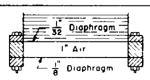
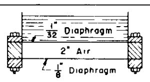
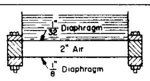
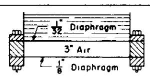
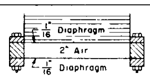
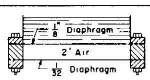
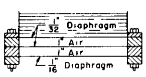
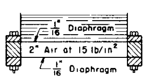
Test EI employed a construction the same as that for Test CQ, except that in Test EI the air space in the assembly was pumped up with air to a gage pressure of 15 pounds per square inch.

It will be noted from Table 16, where the data for these tests are set down, that the merit factor improves with an increase in thickness of air space. At first thought it might be supposed that this is the result of reducing the effective stiffness of the facing diaphragm and hence the swing time, and that consequently it constitutes a demonstration of the principles of mechanical filter theory. However, a further examination shows that the smaller deflections of the backing diaphragm are to a considerable extent compensated for by larger deflections in the facing diaphragms. In other words, the merit of the larger air space probably lay in the fact that it permitted the facing diaphragm to deflect farther before the backing diaphragm was affected.

Except for Test CJ no exact data are available on the deformations of the facing diaphragms in this group of tests. However, the facing diaphragm was almost invariably bulged down until it was in contact with the backing diaphragm. Assuming that this happened in all cases, it was possible to make a rough estimate of the increase in area of the thin facing diaphragm.

TABLE 16

Behavior of Multiple-Diaphragm Constructions with Air Spaces

Test	Composite Structure: Diagram	Thickness of Layers: Facing Diaphragm inches	Thickness of Layers: Air Space inches	Thickness of Layers: Backing Diaphragm inches	Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on: Increase in Deflection	Merit Factors Based on: Increase in Area	Merit Factors Based on: Energy, Averaging Analysis	Merit Factors Based on: Energy, Individual Analysis
1-Ounce Charge of TNT at 12 Inches, Configurations A and B													
Z-1 Z-2		0.027 0.027	1 1	0.121 0.121	0.148 0.148	2.31	21.2 15.6	3750 2800	2720* 2070*	1.02	1.31 1.35	1.12 1.10	1.38 1.35
1-Ounce Charge of Tetryl at 12 Inches, Configurations C and D													
DG-1		0.031	1	0.132	0.163	2.70	25.8	4300	2530	0.90	1.16	1.51	1.70
CJ-1		0.027	2	0.122	0.149	2.83	28.5	4740	2670	1.05	1.89	1.64	1.78
CC-1 CC-2		0.028 0.028	2 2	0.122 0.122	0.150 0.150	2.82	28.3 23.6	4700 4150	2370 6570	1.14	2.11 0.68	1.77 0.58	1.98 0.63
DF-1		0.031	3	0.126	0.157	2.76	26.9	4500	1640	1.33	2.30	2.40	2.74
CQ-1		0.062	2	0.062	0.124	3.17	34.7	5650	993	1.33	3.04	**	5.69
DE-1†		0.125	2	0.030	0.155	2.78 2.78	27.3 27.3	4550 4550	600 4950	1.53 0.78	4.02 0.81	**	7.58 0.92
DZ-1		0.031	1 0.031 diaph. 1	0.062	0.124	3.17	34.8	5650	1320	1.20	2.35	**	4.28
EI-1		0.061	2††	0.062	0.123	3.18	35.1	5660	894	2.24	2.88	**	6.33

* These values are based on an assumed average yield stress of 51,000 pounds per square inch; see the first footnote to Table 4.

** Averaging analyses are not applicable to diaphragms less than 1/8 inch thick.

† Where double values are shown in this row, the upper one is based on the thin backing diaphragm and the lower one is based on the inner 1/8-inch diaphragm.

†† The pressure of the air in this space was 15 pounds per square inch above atmospheric pressure.

From this, an examination of the product of the thickness *h* and ΔA for each diaphragm was made; see Table 17. For a given steel this product is proportional to the total energy absorbed, including that in both facing and backing members. Comparison of these values reveals that in Test CQ, where the facing and the backing diaphragm were of the same thickness and the combined thickness was only 1/8 inch, considerably less total energy was absorbed than in either Test CJ or DE where the combined thickness was 5/32 inch and the two members were of equal thickness. Since in all these tests the configuration

TABLE 17

Comparison of Energy Values Absorbed by Facing and Backing Diaphragms

A charge of 1 ounce of tetryl was exploded on the axis 12 inches distant, Configuration C.*

Test	Thickness of Facing Diaphragm inches	Thickness of Air Space inches	Thickness of Backing Diaphragm inches	Increase in Area ΔA square inches		Equivalent Thickness	Merit Factor*	Product of Actual Thickness and ΔA		
				Facing Diaphragm	Backing Diaphragm			Facing Diaphragm	Backing Diaphragm	Total
DG-1	0.031	1	0.132	25.0**	22.3	0.163	1.16	0.78**	2.94	3.72**
CJ-1	0.027	2	0.122	73.7	15.1	0.149	1.89	1.99	1.84	3.83
CC-1	0.028	2	0.122	33.0**	13.4	0.150	2.11	0.92**	1.63	2.55**
DF-1	0.031	3	0.126	40.0**	11.7	0.157	2.30	1.24**	1.47	2.71**
CQ-1	0.062	2	0.062	32.0	11.4	0.124	3.04	1.98	0.71	2.69
DE-1	0.125	2	0.030	33.7	6.8	0.155	4.02† 0.81†	4.21	0.20	4.41
DZ-1	0.031 center diaphragm	1 0.031 1	0.062	62.0 39.8	14.8	0.124	2.35	1.92 1.23	0.92	4.07
EI-1	0.061	2††	0.062	34.0	12.2	0.123	2.88	2.07	0.76	2.83

* These values were taken from the column "Merit Factor Based on Increase in Area" in Table 16.

** Measurements of the change of area of the facing diaphragms were not made for these three tests because in each case the facing diaphragms sheared off at least part way around the rim. For these cases ΔA was estimated to be about equal to $\pi z^2/2$ where z is the thickness of the air space plus the deflection of the backing diaphragm. This formula gives the change in area from a plane diaphragm to the surface of a corresponding cone of height z to within a few per cent, but the diaphragm may not have taken on an exactly conical shape, and it may have torn before reaching the backing diaphragm. If the final shape of the diaphragm had been an outer segment of a sphere the corresponding change of area would have been πz^2, but the more conservative expression $\pi z^2/2$ was used here.

† The high merit factor of 4.02 was based on the unusually thin backing diaphragm while the low value of 0.81 was based on the thick facing diaphragm.

†† The pressure of the air in this space was 15 pounds per square inch above atmospheric pressure.

was the same, it appears that on a purely comparative basis Construction CQ was the most effective.

In the practice of electronics or acoustics, it is known that an effective procedure for rejecting certain frequency bands is to use successive filter sections of identical design. To this extent the advantage obtained in Test CQ appears to bear out the predictions of mechanical filter theory. It is not adequately explained by simple static considerations.

Test DZ, which used three diaphragms and two 1-inch air spaces, as shown in Figure 33, shows a higher merit factor than some of the constructions which included only one pair of diaphragms and a single 2-inch air

---

* Data for Test Z were omitted because TNT was used instead of tetryl. Data from unprotected diaphragms of thickness equal to the equivalent thickness of Test Z indicate that the change in area from TNT should be increased by about 35 per cent to obtain the corresponding values for tetryl for the first shot.

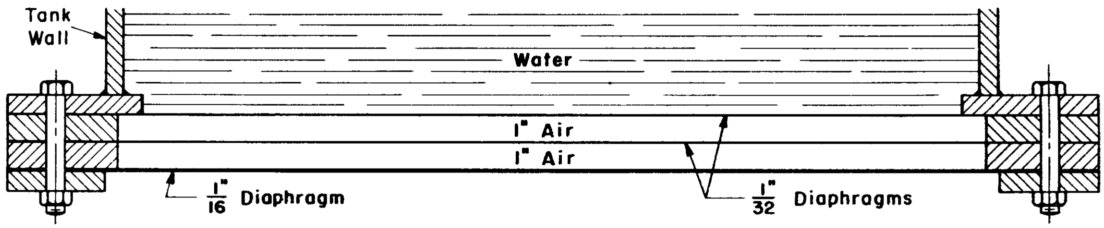


Figure 33 - Schematic Diagram of Composite Assembly for Test DZ

space; however, reference to the last column of Table 17 indicates that the 3-diaphragm construction apparently accepted and absorbed more total energy than the 2-diaphragm constructions. The result is therefore inconclusive in determining whether there was acoustic filter action.

Test EI, in which the pressure of the confined air was increased to 15 pounds per square inch above atmospheric pressure, was designed to afford another means of verifying the application of the filter theory. It should be compared with Test CQ in which an identical construction was used except that the air was at atmospheric pressure. Presumably the increased stiffness of the air should have decreased the swing time of the facing diaphragm, and to that extent made the construction somewhat more susceptible to damage. However, since the stiffness of the air space is still fairly small compared to the stiffness of the diaphragm the change should not be great. The observed results are inconclusive.

No attempt has been made to estimate exactly the amount of energy which went into compression of the confined air in the steel-air-steel assemblies, because of uncertainties in the residual volume. However, a rough estimate in the case of Tests CQ and DE showed values of the order of 14,000 to 20,000 inch-pounds. This is not more than 10 or 12 per cent of the total energy absorbed by the two steel diaphragms in these constructions, assuming a yield stress equal to the static value. In Test EI, where the air was under an initial compression, the amount of energy thus absorbed by the air was roughly doubled. However, this energy was still a rather small fraction of the total work done on the diaphragm. It is apparent that the variations resulting from changes in the thickness or pressure of this confined air body can produce only small alterations in the response of the system.

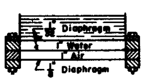
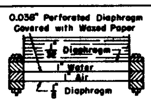
MULTIPLE-DIAPHRAGM CONSTRUCTIONS WITH AIR AND LIQUID FILLING

To carry still further the comparison with the protective structures actually used on ships, two assemblies were made up, CG and CH in Table 18, in which there were three layers of steel but the intervening space next to the charge was filled with water, while that away from the charge was filled with air. The results are set down in Table 18.

TABLE 18

Behavior of Multiple-Diaphragm Constructions with Water-Air Filling

A charge of 1 ounce of tetryl was exploded on the axis 12 inches distant, Configurations C and D.

Test	Composite Structure				Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on			
	Diagram	Thickness of Diaphragms,* inches								Increase in Deflection	Increase in Area	Energy	
		Facing	Center	Backing								Averaging Analysis	Individual Analysis
CG-1		0.026	0.026	0.126	0.178** 0.306	2.55** 1.98	23.3** 12.5	3950** 1750	2320 2320	0.98** 0.76	1.69** 0.91	1.49** 0.72	1.70** 0.75
CG-2					0.178** 0.306		19.8** 10.9	3400** 1690	2340 2340		1.54** 0.84	1.38** 0.66	1.45** 0.72
CH-1		0.027	0.038	0.122	0.180** 0.284	2.54** 2.04	23.0** 13.6	3850** 2000	1660 1660	1.16** 0.93	2.30** 1.36	2.02** 1.12	2.32** 1.20

* In each test there was 1 inch of water between the facing diaphragm and the center diaphragm and 1 inch of air between the center diaphragm and the backing diaphragm. In Test CH-1 the center diaphragm was perforated and covered with waxed paper.

** These values were computed by omitting the weight of water in the diaphragm structure. The water may be replaced by oil fuel on a ship. In the unstarred values the weight of the water was included, and low merit factors resulted.

The merit factors derived will depend on whether it is considered necessary to include the weight of the liquid as part of the protective system. However, as the liquid on a ship may be oil fuel, which has to be carried in any event, its weight may be omitted. Under this assumption, a ratio of merit of the order of 1.5 is obtained in Test CG; this ratio is even higher, about 2.0 or more, for Test CH, in which the middle diaphragm was perforated. The merit factor for Test CG is slightly less than for Test CJ* in which the middle diaphragm was omitted and no liquid was used, and considerably less than for Test DF with its 3-inch air space. It is therefore concluded that, although the division of the metal into two separate bulkheads may be of some help, it is mainly the presence of the thicker air space which accounts for the benefit. Filling part of it with liquid (water) appears to be of no benefit;** on the contrary, this would reduce the protective effect, if the weight of the liquid were considered.

COMBINATIONS OF WOOD WITH AIR SPACES

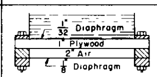
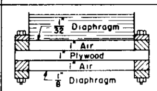
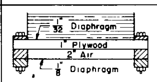
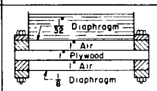
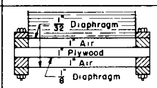
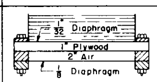
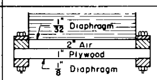
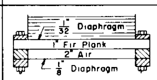
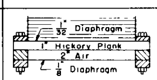
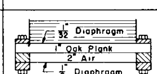
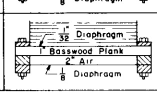
Since the two most successful means of protection developed were multiple-bulkhead constructions containing air spaces, and constructions containing wood, a final step was to try arrangements in which both protective devices were used. A series of diaphragm models were accordingly made up,

* See Table 16 on page 76.

** The value of the liquid in reducing the fragmentation effect is not considered here.

TABLE 19

Behavior of Composite Assemblies of Clamped Wood with Air Spaces

Test	Composite Structure		Equivalent Thickness h_q of Single Plate inches	Equivalent Deflection ΔZ_q inches	Equivalent Increase in Area ΔA_q square inches	Equivalent Energy in Single Plate Ω_q in-lb/lb	Actual Energy Absorbed by Backing Diaphragm Ω in-lb/lb	Merit Factors Based on			
	Diagram	Description of Filling*						Increase in Deflection	Increase in Area	Energy: Averaging Analysis	Energy: Individual Analysis
	1/2-Ounce Charge of Tetryl in Contact, Configuration E										
CU-1		1-inch plywood disk, clamped, 2 inches of air	0.240	1.88	9.4	1640	311	1.88	5.21	4.65	5.27
DK-1		1 inch of air, 1-inch plywood disk, clamped, 1 inch of air	0.233	1.91	9.7	1720	250	1.46	4.03	5.79	6.88
DN-1		1-inch plywood disk, clamped, 2 inches of air	0.233	1.91	9.7	1720	370	1.43	3.02	4.07	4.65
	1-Ounce Charge of Tetryl at 12 Inches, Configuration C										
DI-1		1 inch of air, 1-inch plywood disk, clamped, 1 inch of air	0.231	2.23	17.4	2790	700	1.46	2.72	3.45	3.99
DL-1†		1 inch of air, 1-inch plywood disk, 1/8-inch diaphragm, 1 inch of air	0.263	2.10 2.10	14.9 14.9	2280 2280	540 1350	0.99 0.94	2.07 1.30	**	4.22 1.69
DM-1		1-inch plywood disk, clamped, 2 inches of air	0.232	2.22	17.3	2760	1130	1.19	1.82	2.16	2.44
DW-1		2 inches of air, 1-inch plywood disk	0.225	2.27	17.9	2900	1360	1.17	1.99	1.84	2.13
EE-1		1-inch fir plank, 2 inches of air	0.205	2.37	19.9	3280	1100	1.27	2.34	2.58	2.98
EF-1		1-inch hickory plank, 2 inches of air	0.237	2.20	16.9	2700	557	1.44	3.93	4.19	4.85
EG-1		1-inch oak plank, 2 inches of air	0.241	2.18	16.6	2620	830	1.34	2.59	2.75	3.16
EH-1		1-inch basswood plank, 2 inches of air	0.201	2.39	20.4	3350	732	1.45	3.58	3.95	4.58

* All backing diaphragms in this group were about 1/8 inch thick, except in Test DL in which the backing diaphragm was about 1/32 inch thick. All facing diaphragms were about 1/32 inch thick.

** Averaging analyses are not applicable to diaphragms less than 1/8 inch thick.

† Where double values are shown in this row, the upper one is based on the thin backing diaphragm and the lower one is based on the center 1/8-inch diaphragm.

each model consisting of three diaphragms of steel and wood combined in various relative positions. The data are set down for comparison in Table 19.

The most encouraging feature about this set of experiments, aside from the relatively high merit factors of these constructions, was the fact that the protection provided by each of the two devices apparently supplemented that of the other. The wood when used in combination with an air space was always better than the air space alone or better than the wood alone.

Tests CU and DN of Table 19 were made for verification. Where the value of ΔA is as small as on these diaphragms an accurate measurement is difficult and therefore it was considered desirable to recheck the measurement. Although there is some variation between the results of these two tests, it is clear that this type of construction offers excellent protection.

Of the various woods used in Tests EE to EH, hickory proved to be the best, with basswood second. The principal feature of these wood-steel constructions is that the wood must undergo considerable deflection before it can be reinforced to any great extent by the steel backing diaphragm. It may be that hickory and basswood absorb the energy over a larger range of deflections than woods of other species.

Test DM in Table 19 may be compared with Test DF in Table 16 on page 76, in which the entire intervening 3-inch space between the diaphragms was filled with air and no wood was used. The protection afforded by Assembly DM is better in the sense that the deflection of the backing diaphragm is less; 1.87 inch as compared to 2.07 inches.* The merit factor of Test DM, however, is not quite as good as that of Test DF because of the increased weight of the former.

In the case of Test DI, where 1 inch of plywood was placed in the center of the 3-inch air space, both the figure for ΔA and the merit factor showed an improvement over the results for Test DF with the 3-inch air space alone. The same is true for the last four tests in Table 19, in which 1-inch layers of various wood species were backed by 2-inch air spaces.

It is probably significant that the order of merit among the different species of wood in this series is different from that in the preceding comparisons. Most strength tests on wood compare performance up to the breaking point. In the explosion protection screens, considerable work is done on the wood after the initial failure has occurred. This is particularly true in the constructions listed in Table 19, where the wood was required to deflect 2 inches before it touched the backing diaphragm. The properties of wood in this range are less well known, although, as previously noted, it had been suspected that basswood might have useful properties in this type of construction. The 1-inch plywood did not give as good results as any of the disks made up from tongued and grooved planks.

---

* See Table 5 on page 34.

One of the objectives of this last series of tests was to determine the most suitable distribution of the air space and of the wood. The results in Table 19 show little advantage for any one arrangement. The merit factors for Tests CU and DN, where the plywood is in front of the air space, show little difference from that of Test DK, where it was centered in the air space. Test DI is somewhat better than Test DM, indicating that for a non-contact shot there may be some advantage in the additional air space in front of the wood. Test DL, in which a heavy diaphragm backing the center layer of wood was used, seems to have no compensating advantage over Test DI; the additional weight of steel reduced the merit factor.

MISCELLANEOUS

A number of additional experiments are reported in Tables 4, 5, and 6, which did not fall into any of the classifications hitherto listed. Among these may be mentioned two tests on concrete, BX and BY; see Table 6 on pages 36 and 37. The former had a filler made up with a standard 1-2-4 mix in which a pea-gravel aggregate was used; the filler in the latter was a similar mix with a special light-weight aggregate. Both concrete disks gave appreciable protection but not enough to justify the added weight.

Several tests were also made in an attempt to force the explosion to do more work in distorting the facing diaphragm by one device or another. Tests CW and DB are examples; see Table 5 on pages 34 and 35. These were not particularly successful.

Following the rather successful experiments with combinations of air spaces and wood, special designs for 1/16-scale box or caisson models were prepared, by the use of the general scheme which had been followed by the Bureau of Ships for a number of years in tests of this kind at the Norfolk Navy Yard.

Three such models were built by the Taylor Model Basin and were tested at Norfolk, but with indifferent results; see Appendix 3. It is hoped to describe this phase of the work more fully in a separate report.

Two 1/16-scale caisson models were also built at Norfolk (15) (16) to designs supplied by Bond and Mason. Details of the results of these tests are not available.

DISCUSSION OF RESULTS

It is probably beyond the scope of this report to account for the fact that the static data, such as the measured yield strengths, do not bring the dynamic test observations more closely into line. Among the unknowns in the problem are the effect of strain rate and the effect of thinning in the diaphragm as deflection occurs. Merely as a matter of speculation it is suggested that perhaps the effect of strain rate is greater when the initial static yield stress is lower, so that the two factors compensate each other.

Time-displacement records taken on a number of the test diaphragms showed that the pressure from the explosion is applied over a much longer period of time than would have been expected from simple theory. Free-field pressure measurements in other tests have shown that the duration of the initial explosion pressure pulse is about 50 microseconds. This is a very short time compared to the estimated swing time (13) for these diaphragms of 1.5 millisecond, or 1500 microseconds. However, the displacement records for this particular experimental setup indicate that the pressure is maintained or is recurrent over several milliseconds, which is of the same order as the swing time of the diaphragms. Apparently a successful application of the mechanical filter theory must await a more favorable experimental setup, or must take into account longer time constants in the pressure wave than had been anticipated. Furthermore, if the time duration of the pressure for the small charges is as great as these tests appear to indicate, the duration for the large charges may also be too long to be successfully handled by practical ship construction. All these conclusions, however, await some confirmation in an open-water test where the pressure is not confined by tank walls.

The studies on substitute materials have shown no material except wood which approaches the effectiveness of steel in absorbing explosive energy. It seems possible that the success of wood in the constructions reported here is due to two factors which have not hitherto been present in similar tests. First, the wood was in all cases backed up and closely supported by a steel member. In consequence, the initial failure of the wood by no means represented the end of its usefulness. A good illustration of the importance of this consideration may be obtained by referring to Test CV, Table 6, page 37, in which the backing diaphragm was omitted. This construction ruptured on the first shot, and in consequence represented a failure by almost any method of evaluating damage.

Another consideration is that in almost all cases the constructions were not deflected to a point close to rupture. It seems likely that wood is proportionally more effective for small deflections than it would be for larger deflections. If this is the case it suggests the desirability of using wood in inner bulkheads of multiple constructions where the deflections are likely to be less.

The possibility of reflecting the explosive energy is mentioned in the proposals made by Bond and Mason. At this point it is necessary to reiterate that such reflection presupposes that the structure can temporarily store the energy in the form of an elastic deflection and return it to the water without suffering too much permanent damage. The possibility of using coil springs for this purpose was considered, but was rejected because impossibly large springs were found necessary. As has been noted, rubber and felt were tried in various forms without much success.

The simplest and most satisfactory protective construction consisted of a diaphragm stretched over a confined air space. Even when previously compressed, the air did not absorb enough energy in compression to take care of the explosive energy, but the diaphragms in these cases were able to absorb the remainder in the form of plastic work. At the same time, the diaphragm exhibited certain characteristics which were similar to those of a spring.

In general, substantially the same amount of damage was done by non-contact explosions consisting of a charge of 1 ounce as by contact explosions of one-half ounce of charge. As was to be expected, the damage by the contact explosions was more localized.

As the energy absorption in the various reference diaphragms was carefully determined, these data afford a check on Roop's nominal theory (14) of underwater explosion damage. The free-water conditions for which the solid angle theory of Focke and Hartmann (17) were derived do not obtain here, especially in any comparison between the effect of small charges of TNT and tetryl. This matter is discussed at some length in Appendix 2.

SUMMARY AND CONCLUSIONS

Despite the rather severe limitations of the test procedure and the considerable number of apparent discrepancies in the test results, it is nevertheless possible to draw certain conclusions from the data.

Attempts to apply mechanical-filter theory to the design of protective constructions in the cylindrical test tank have for the most part been unsuccessful. The tests which appeared to offer the best application of the theory were those employing pure inertia, and the corresponding assemblies were found to be without merit.

These tests bear out previous investigations which established the merit of multiple-bulkhead systems with air spaces between. With the exception of sawdust no simple filler material was found more suitable than a simple air layer.

The tests verified the fact, already known from previous small-scale and full-scale tests, that wood possesses considerable protective power against contact or non-contact explosions.

Placing the wood behind a steel facing enhances its protective value and prevents rotting of the wood. Placing the wood in front of another steel facing supports it while the energy is being absorbed in shredding the fibers. Wood used as a protective layer should be worked in as structural members, securely held in place, rather than as filling.

Greater spacings between diaphragms appear desirable and there is a suggestion that the optimum distribution of steel among bulkheads or diaphragms warrants further study.

REFERENCES

(1) "The Application of Mechanical Impedance Theory to the Design of Detonation Shields and Armor Plate, Case 19879," by W.L. Bond and W.P. Mason, Bell Telephone Laboratories Technical Memorandum MM-39-326-101, 22 December 1939.

(2) "Small Scale Models of Detonation Shields," by W.P. Mason, Bell Telephone Laboratories CONFIDENTIAL Technical Memorandum MM-40-160-30, 1 April 1940.

(3) BuShips CONFIDENTIAL Letter BB/S1-1(7-9-DY1) of 5 August 1940 to EMB, forwarding a copy of Bell Telephone Laboratories CONFIDENTIAL Technical Memorandum "Small Scale Models of Detonation Shields," by W.P. Mason, MM-40-160-71, 20 June 1940.

(4) Bureau of Construction and Repair and Bureau of Engineering joint CONFIDENTIAL Letter C-S81-3(4-18-DY1) of 20 April 1940 to EMB.

(5) BuShips CONFIDENTIAL Letter C-S81-3(4-18-DY1) of 20 April 1940 to Electrical Research Products, Inc., copy to EMB.

(6) "Welding Test 194 - STS Cylinders Subjected to Explosive Impact," by J.W. Day, EMB CONFIDENTIAL Report R-117, March 1940. "Welding Test 194 - STS Cylinders Subjected to Explosive Impact; Supplement," by J.W. Day, EMB CONFIDENTIAL Report R-118, May 1940. "Welding Test 194 - STS Cylinders Subjected to Explosive Impact; Second Supplement," by J.W. Day, TMB CONFIDENTIAL Report R-125, January 1942.

(7) "Torpedo Protection Systems, Preliminary Data on the Underwater Shock Wave," TMB CONFIDENTIAL Report R-49, December 1941.

(8) BuShips Letter S81-3 of 23 January 1942 forwarded to the David Taylor Model Basin a set of pencil notes written by N. Artsay entitled "Notes on Experiments with Underwater Explosions," dated 5 July 1941. These notes are essentially the same as one section of the so-called Makaroff report of somewhat later date. A photostat copy of the pencil notes is to be found on TMB File C-S81-3, Vol. 2; a copy of the Makaroff report is available in the TMB Library.

(9) "Early and Ultimate Damage due to Underwater Explosions against 10-Inch Diaphragms," by G.E. Hudson, Ph.D., TMB CONFIDENTIAL Report 509, August 1943.

(10) "Plastic Strain and Deflection Tests on Clamped Circular Steel Plates 20 Inches in Diameter," by A.N. Gleyzal, Ph.D., TMB Report R-142, May 1944.

(11) "Protection against Underwater Explosion, Plastic Deformation of a Circular Plate," by A.N. Gleyzal, Ph.D., TMB Report 490, September 1942.

(12) "Effects of Underwater Explosions, General Considerations," by Prof. E.H. Kennard, TMB CONFIDENTIAL Report 489, September 1942.

(13) "The Effect of a Pressure Wave on a Plate or Diaphragm," by Prof. E.H. Kennard, TMB CONFIDENTIAL Report 527, March 1944.

(14) "The Design of Ship Structure to Resist Underwater Explosion - Nominal Theory," by Captain W.P. Roop, USN, TMB CONFIDENTIAL Report 492, August 1943.

(15) BuShips CONFIDENTIAL Letter C-S81-3(1/27-DYr) of 31 January 1941 to Electrical Research Products, Inc., with enclosures; copy to TMB.

(16) BuShips CONFIDENTIAL Letter C-S81-3(DYr) of 9 April 1941 to Electrical Research Products, Inc., with enclosures; copy to TMB. This letter requested that two 1/16-scale caisson models, incorporating the ideas of References (1), (2), and (3), to be tested with 3/4-pound charges of TNT, be designed for construction and test in comparison with previous small-scale caisson models.

(17) BuOrd Memorandum on Solid Angle Theory, by G.K. Hartmann, S68(Re6b) of 22 April 1942.

(18) "The Vertical Motion of a Spherical Bubble and the Pressure Surrounding It," by Prof. G.I. Taylor, F.R.S., TMB CONFIDENTIAL Report 510, August 1943.

(19) TMB CONFIDENTIAL Letter C-S81-3 of 24 September 1942 to BuShips.

BIBLIOGRAPHY

"Report of Test of 1934 Half-Scale Torpedo Caissons," by Lt. H.A. Schade, (CC), USN, BuShips CONFIDENTIAL Report, May 1935.

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

Bureau of Construction and Repair Flatfiles 016010, 016011, and 016013.

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

"Report on Underwater Explosions," by Prof. E.H. Kennard, TMB CONFIDENTIAL Report 480, October 1941.

APPENDIX 1

DERIVATION OF ENERGY ABSORPTION BY THE AVERAGING METHOD

TEST DATA

The test results for the six configurations of charge and target, as listed in Tables 1, 2, and 3 of the report on pages 29 to 31, are presented in Tables 20, 21, and 22, and are taken as a starting point for this discussion.

TABLE 20

Observed Plastic Deformation and Derived Energy Absorption, U, for Reference Diaphragms Attacked by 1 Ounce of TNT at 12 Inches Distance

Nominal Thickness h inches	Configuration A				Configuration B			
	Static Yield Stress σ_y kips/in^2	Number of Tests	Increment of Area ΔA square inches	U inch-kips	Static Yield Stress σ_y kips/in^2	Number of Tests	Increment of Area ΔA square inches	U inch-kips
1/16	27.8	1	53.3	93				
1/8	50.7	6	25.3	160	51.4	5	19.5	125
3/16	48.7	1	15.1	138	48.7	1	10.2	93
1/4	32.3	1	12.2	99	32.3	1	7.7	62
3/8	35.0	1	7.2	94	35.0	1	10.6	139
			Average	116.8			Average	104.8

TABLE 21

Observed Plastic Deformation and Derived Energy Absorption, *U*, for Reference Diaphragms Attacked by 1 Ounce of Tetryl at 12 Inches Distance

Nominal Thickness h inches	Configuration C				Configuration D			
	Static Yield Stress σ_y kips/in²	Number of Tests	Increment of Area ΔA square inches	U inch-kips	Static Yield Stress σ_y kips/in²	Number of Tests	Increment of Area ΔA square inches	U inch-kips
1/16	28.7	2	72.7	130				
1/8	45.3	5	35.3	200	45.8	4	28.2	161
3/16	38.1	1	21.3	152	38.1	1	21.5	154
1/4	41.4	2	16.1	167	41.4	2	13.4	139
5/16	43.6	2	10.0	136	43.6	2	7.9	108
3/8	36.8	2	9.0	124	36.8	2	10.8	149
			Average	151.5			Average	142.2

TABLE 22

Observed Plastic Deformation and Derived Energy Absorption, *U*, for Reference Diaphragms Attacked by 1/2 Ounce of Tetryl in Contact with the Diaphragm

Nominal Thickness h inches	Configuration E				Configuration F			
	Static Yield Stress σ_y kips/in²	Number of Tests	Increment of Area ΔA square inches	U inch-kips	Static Yield Stress σ_y kips/in²	Number of Tests	Increment of Area ΔA square inches	U inch-kips
1/8	42.5	5	19.2	102	43.8	4	16.5	90
3/16	51.9	2	12.6	123	51.9	2	9.9	96
1/4	40.8	2	10.1	103	40.8	2	9.4	96
5/16	41.4	1	6.1	79	41.4	1	7.4	96
3/8	37.9	1	5.4	77	37.9	1	5.4	77
			Average	96.8			Average	91.0

The total energy *U* absorbed by the diaphragm, by the simple theory of TMB Report 490 (11), equals the product of the plastic increase in area of the diaphragm by the tension opposing it. This tension equals the product of the thickness by the plastic stress. Since the strains are not great as compared with the elongations occurring in the static tensile test, and since strain-hardening is thus not very great, the stress is taken simply to be the yield point as found in the standard tensile test.

The material varied a great deal in characteristics; the observed yield strength ranged from less than 30,000 to more than 60,000 pounds per square inch in individual specimens. The value of U is given in Tables 20 to 22 for each nominal thickness for which it was measured in each of the six configurations.

EFFECT OF DIAPHRAGM THICKNESS

In order to make the thickness effect apparent in these quite scattered data, the average value of U for each configuration has been found and for each thickness the individual value of U has been expressed as a fraction of the average for that configuration. The results are given in Table 23 and in Figure 34.

A systematic variation is strongly suggested, but it is difficult to determine specifically what it is.

A pronounced drop in energy absorption toward small values of thickness occurs consistently in four out of the six configurations. If the other two series had extended to a thickness of 1/16 inch the drop might have been seen in these as well.

The chief feature shown in Figure 34 is the decrease of U as the thickness increases from 1/8 to 3/8.

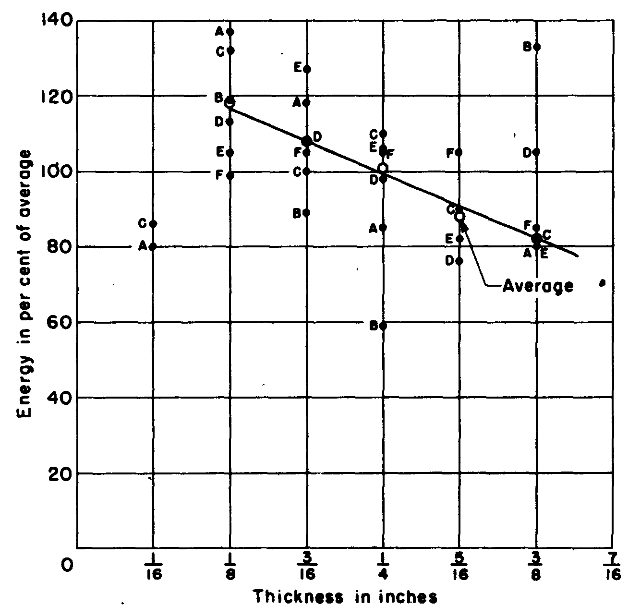


Figure 34 - Energy Absorption as a Fraction of the Average for Each Configuration, Plotted on Thickness

The average energy for a given configuration was calculated. This configuration includes several thicknesses. The individual points shown represent percentages of these average values.

The number of cases is considered not sufficient to define the thickness effect accurately for each configuration separately.* The values for each thickness from all configurations have therefore been averaged, and these spots are seen from Figure 34 to lie fairly well in the line

$$U_h = U_{0.25}\left[1 - 1.45(h - 0.25)\right] \quad [1]$$

* The opposite assumption has been made in the body of the report where this procedure has been followed by the use of so-called calibration curves of which Figure 23 on page 50 is typical.

TABLE 23

Thickness Effect, Expressed as Energy Absorption in Per Cent of the Average

Nominal Thickness h inches	Per Cent of Average Energy Absorbed — Configuration						Average Percentage
	A	B	C	D	E	F	
1/16	80		86				
1/8	137	119	132	113	105	99	118
3/16	118	89	100	108	127	105	108
1/4	85	59*	110	98	106	105	101
5/16			90	76	82	105	88
3/8	80	133*	82	105*	80	85	82

* These "wild" values have been omitted in averaging for each thickness.

TABLE 24

Values of $U_{0.25}$

This table gives the energy absorption in inch-kips for h = 0.25 inch, as inferred from measurements on diaphragms of various thicknesses.

Nominal Thickness h inches	Energy Absorption in inch-kips — Configuration					
	A	B	C	D	E	F
1/16	*		*			
1/8	135	106	169	136	86	76
3/16	127	85	139	141	113	88
1/4	99	62	167	139	103	96
5/16			150	119	87	106
3/8	115	*	151	*	94	94
Average	119 ± 5**	84 ± 9	155 ± 4	134 ± 3	97 ± 3	92 ± 3

* A value considered erratic has been omitted.

** In each case the value following ± is the probable error of the average which takes into account only the internal consistency of the data shown here.

where $U_{0.25}$ is the energy absorbed by a 1/4-inch diaphragm. This formula is therefore proposed for use in the calculation of energy values for effective thicknesses of 1/8 inch and over.

To obtain an estimate for each configuration of the best value of $U_{0.25}$, the energy values in Tables 20 to 22 have been corrected by the use of the thickness formula to terms of the mean thickness of 1/4 (0.25) inch, with the results shown in Table 24. In other words the values of $U_{0.25}$ for use in

Equation [1] have been inferred from U_h and h for various values of h. The last line of Table 24 gives a separate value of $U_{0.25}$ for each configuration; in each case this is the value thus established and chosen for use in the reduction of data from tests made in that configuration.

The best value obtainable from the present data for energy absorption in a simple unscreened diaphragm of any thickness of 1/8 inch or more in a given configuration is now to be found by applying to the appropriate average from Table 24 a correction as in Equation [1] for the departure of the given thickness from the datum value of 1/4 inch. This is then used in inferring the ratio R_1, as described on page 49 of the text, by dividing the corrected energy absorption for the unscreened diaphragm by the observed energy absorption in the screened diaphragm.

The ratio R_1, representing the effect of a given screen, is then to be compared with the benefit obtainable from an equal weight of steel, represented by the ratio R_2. R_2 is calculated by assuming, first, that the capacity of a steel diaphragm for plastic absorption of energy is proportional to its thickness. If the thickness were increased from h_1, its value in the test, to h_2, the thickness of a weight of steel equivalent to that of the entire composite construction, the absorption of a given amount of energy as in a given configuration would now utilize a smaller fraction of the capacity, which is increased in the ratio h_2/h_1. Beyond this there is also the effect of thickness on the transmission of destructive energy of the explosion into the diaphragm target, as affected by the mobility of the target. This effect is seen in Figure 34. This multiplies the effect of the increased thickness of steel in the proportion

$$\frac{1 - 1.45(h_1 - 0.25)}{1 - 1.45(h_2 - 0.25)}$$

The whole increase in protective effect R_2 caused by an increase in thickness from h_1 to h_2 is then

$$R_2 = \frac{h_2[1 - 1.45(h_1 - 0.25)]}{h_1[1 - 1.45(h_2 - 0.25)]} \qquad [2]$$

$$R_2 = \frac{\dfrac{1.362}{h_1} - 1.45}{\dfrac{1.362}{h_2} - 1.45} \qquad [2a]$$

If h_1 = 1/8 inch, the numerator is 9.45.

The significance of these results may be clarified by the following comment. The thickness of a diaphragm exposed to underwater explosion naturally controls its deflection in a given configuration of charge and target.

It might be natural to expect the energy transferred to the target to be unaffected by the thickness, and since nominally the energy is calculated by a formula which contains the thickness as a factor, a reduction of thickness would have to be offset by a proportionately increased increment of the increase in area ΔA.

Figure 34, however, shows that as the thickness increases not only does the area increment ΔA diminish but even the product of these two quantities diminishes. This indicates that the thicker diaphragms receive or accept less energy. This is explained by supposing that the diaphragm of smaller mobility either passes the energy on to its supports or possibly reflects it back into the water. If the linear formula could be extrapolated to zero energy absorption, it would indicate that a diaphragm 0.96 inch thick would show no permanent deformation in the given configurations. This result is not unreasonable; the circular STS walls of the test tank are 3/4 inch thick and do, in fact, show no yielding. Their cylindrical form and high yield point, however, prevent direct comparison with the flat medium-steel diaphragms under test.

Extrapolation in the opposite direction to small thickness would be more dubious; the data for thicknesses less than 1/8 inch are meager, but such as they are they suggest that the linear relation cannot in any case be extended in that direction.

APPENDIX 2

APPLICATION OF THE NOMINAL THEORY OF TMB REPORT 492 TO EXPLOSIONS IN A PARTLY CONFINED SPACE

EFFECT OF DISTANCE OF CHARGE FROM TARGET

Since it may be assumed that the weight of the charge is a linear factor throughout, the effect of the half-size charges in the contact shots in Configurations E and F may be allowed for by multiplying the energy absorption by 2. When this is done it leads to the conclusion that the contact charge delivers 23 per cent more energy than a similar charge at a distance of 12 inches, by comparison of Shots 1 with tetryl, or 34 per cent more by comparison of Shots 2 with tetryl.

The ratio of the solid angles subtended in the two cases is about 2.1 to 1. The increase in energy absorbed in moving up from a distance of 12 inches to contact is strikingly less than would be indicated by the increase in the solid angles.

If the test tank were completely closed and were not too large, the position of the charge would presumably make little difference in the energy transferred to the diaphragm. However, the surface of the water in the tank is open; the energy flowing upward from the charge is therefore expended largely in throwing the water upward. The side walls of the tank are massive and are not strained beyond the elastic limit; they therefore retain none of the energy permanently. It may be supposed that sooner or later most of the energy flowing downward from the charge goes into the thin plastic diaphragm forming the bottom of the tank and remains there; for the moment it is assumed that it all does. Regardless of the distance of the charge from the diaphragm, therefore, it is concluded that the effective solid angle subtended at the charge by the target is 2π, or half of the whole. On this basis the whole energy per unit charge projected downward would equal that absorbed by the diaphragm, regardless of the position of the charge.

The actual condition does not reach this extreme, but the assumption of no variation with the position of the charge comes nearer the truth than that of variation with the solid angle. An approximation would be found by taking the 1/3 power of the solid angle.

COMPUTATION OF FIELD COEFFICIENT* FOR THESE TESTS

If it is assumed that the TNT charges delivered only 2/3 the energy of the tetryl charges, configurations with the former explosive may be made comparable with those using the latter by multiplying by 3/2.

If for this setup, where the explosion is confined in a narrow cylinder, the energy delivered to the diaphragm varies as the 1/3 power of the solid angle, the values for the non-contact shots may be made comparable with those for the contact shots by multiplying by 1.3.

On these terms the contact tetryl equivalents for the average values of $U_{0.25}$ given in Table 24 are as given in Table 25.

Dividing these numbers by 2π gives the destructive energy per unit solid angle, and dividing again by the nominal weight of the charge gives the energy in inch-pounds per pound of charge per unit solid angle. This is the quantity designated as F, the field coefficient.

If the apparently smaller values in the second shots made with the diaphragm initially deflected are caused by failure to allow for a 20 per cent increase in plastic stress due to strain hardening of the previous deformation, the values for the second shots may be made comparable with those for the first shots by adding 20 per cent to their energy values.

---

* See TMB Report 492, Reference (14), for the definition and derivation of this term.

TABLE 25

Derived Values of Field Coefficient

Configuration	Shots	Contact Tetryl Equivalent inch-kips	Field Coefficient* inch-kips per pound per unit solid angle	
			Uncorrected	Corrected for Strain Hardening
A	First	232	590	590
B	Second	164	417	500
C	First	202	514	514
D	Second	174	443	532
E	First	97	495	495
F	Second	92	468	562
				Average 532

* The calculated value of the field coefficient given in TMB Report 492, as taken from TMB Report 489, is 345 inch-kips per pound charge per unit solid angle for TNT.

On the basis of all these empirical corrections, values of the field coefficient drawn from the results of tests of the six configurations are assembled in Table 25. The moderate and reasonable assumptions stated are enough to bring the values for all configurations into fair agreement with each other. The values found are also in fair agreement with those drawn from other tests and reported in Reference (14).

This result however is not in agreement with that obtained in open-water tests and reported in TMB Report 509 (9); in that report it was noted that, when the charge was placed at a distance less than a critical value, greatly increased values of field coefficient were found.

A tentative explanation of this fact was suggested in the observed pulsation and migration of the gas globe from the explosion; at the end of the first cycle of compression of the gas globe it is no longer centered on the point at which the explosion occurred, but has moved toward the target. If, as is believed to be the case, an important part of the damage is done in later phases of the action, the error in the calculation of the solid angle is of the right sign, though perhaps not large enough, to explain the underestimate of damage by nominal theory.

In the case of the present tests it is considered possible that the pulsations observed in open water may be prevented by the restricting action of the heavy walls of the test tank. A similar absence of pulsations has been suggested by G.I. Taylor (18) in the case of full-scale explosions; by reason of the failure to scale down the pressure of the atmosphere in most model tests, the pulsations observed on small scale may not be an accurate index of what happens under service conditions.

It is therefore possible that tests conducted in close restriction may produce comparative data on damage of greater validity than tests in open water.

COMPARISON OF THE EFFECTS OF TNT AND OF TETRYL

The configurations for Shots 1 of TNT and tetryl, A and C respectively, and for Shots 2 of those explosives, B and D, differ from each other only in the composition of the charge. The averages for these configurations in Table 24 indicate that tetryl delivers more energy to the diaphragm than TNT in a 1-ounce charge. Comparison of Configurations A and C shows a difference of 30 per cent, and comparison of Configurations B and D, made in the same way, gives an energy value of 60 per cent more for tetryl than for TNT.

It is recognized that small charges of TNT are not completely detonated and it is considered that on this scale tetryl gives better similitude with large charges of TNT than would small charges of TNT itself.

APPENDIX 3

TESTS OF 1/16-SCALE BOX CAISSONS REPRESENTING COMPOSITE WOOD AND STEEL STRUCTURES

This appendix gives some construction and test data on three box models for the 1/16-scale series which were made up for test at the Norfolk Navy Yard (19); see page 82 of this report. These models were composed of rectangular steel plates, some stiffened and some not stiffened, representing the outer shell, the torpedo bulkheads, and the holding bulkhead of a ship protection system. The various steel bulkheads were put together with wood layers as shown in TMB Plans A-5527, A-5528, A-5529, and A-5530, and were then clamped together around their four sides by 40 long bolts, passing through all the layers.

The holding bulkhead had a free area of rectangular shape 18 inches by 36 inches. The layers or compartments were all air filled. The charge was 3/4 pound of TNT for each model, placed 9 inches horizontally from the center of the outer shell panel. In this position it was 16 1/2 inches from the holding bulkhead.

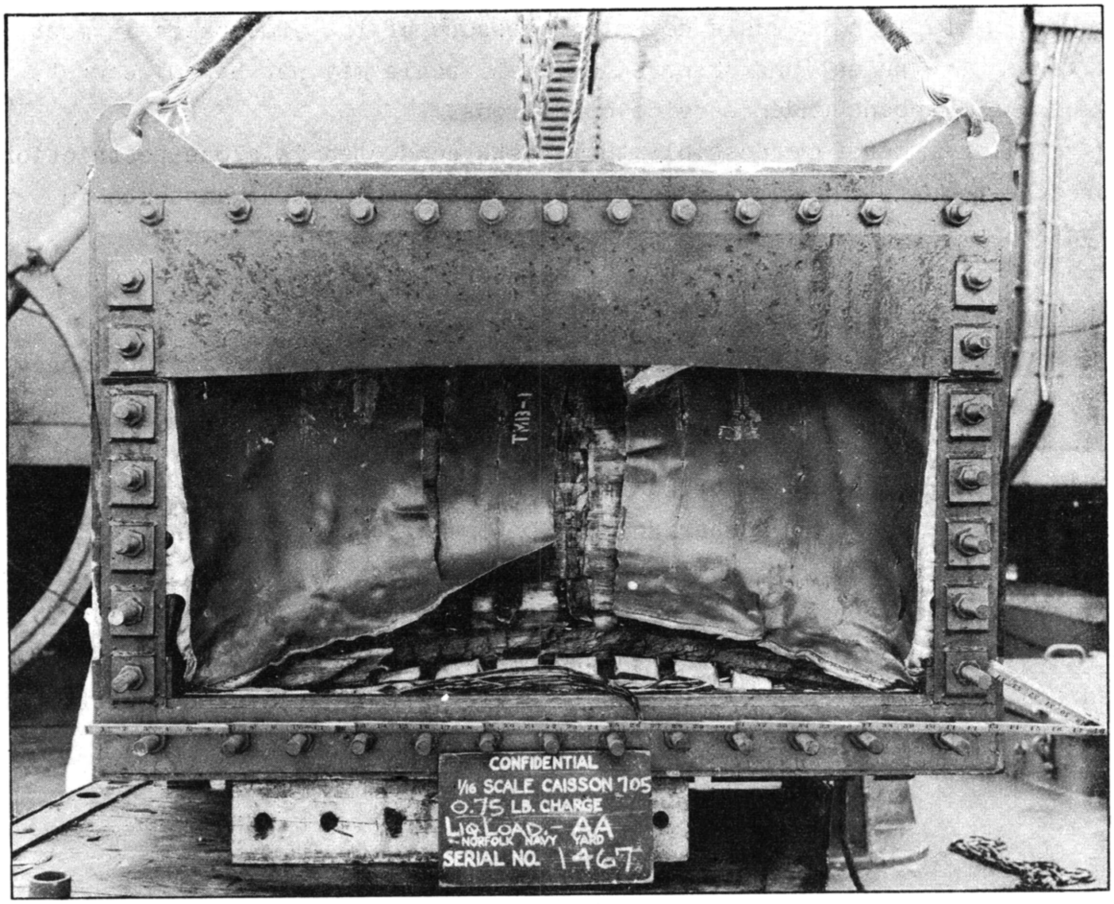


Figure 35 - TMB Model 1 after Firing, with Shell in Place

Figures 35 and 36 show two views of TMB Model 1, Norfolk Model 705, after firing. In this model the outer shell was 0.036 inch thick; Bulkhead 1 was 0.075 inch thick, faced on its outer side with 1 inch of oak; the holding bulkhead was 0.036 inch thick.

The observed deflection in TMB Model 1, sheathed with wood, is 4 inches in the holding bulkhead, larger than in Norfolk Models 583 and 591, of similar construction but not sheathed. The wood sheathing therefore appears to be ineffective in reducing damage to the holding bulkhead.

The other two TMB models were similar in construction and gave a similar result; no striking consequences followed from the presence of the wood, such as were obtained in Tests DI and EG, as shown in Table 19 on page 80.

It is concluded that the mere presence of wood in a torpedo protection system is not at all sufficient to give screening action exceeding or even equaling that of an equal weight of steel. At the same time the tests noted in Tables 14, 15, and 19 indicate that under certain circumstances

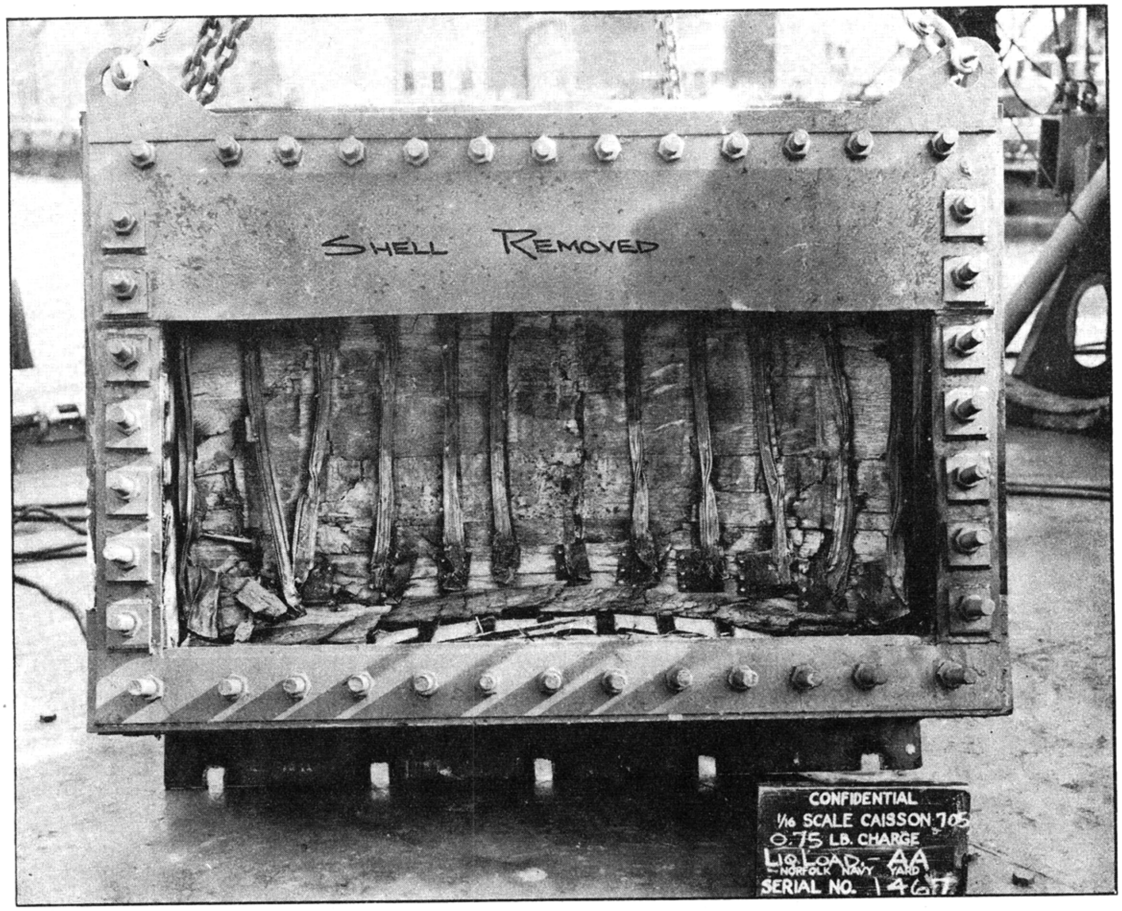


Figure 36 - TMB Model 1 after Firing, with Shell Removed

better screening action can be obtained by the use of wood, than by applying a weight equal to that of the wood to increase the thickness of the steel in a single diaphragm. The details of design necessary to obtain such results on full scale remain to be worked out.

APPENDIX 4

CHARACTERISTICS OF A THIN CIRCULAR DIAPHRAGM

The increase in area of a diaphragm, assuming that upon deflection it is approximately spherical in shape, may be written in terms of the center deflection Z as follows:

$$\Delta A = \pi Z^2$$

Hence the energy absorbed in plastic work is, by Reference (11)

$$U = \sigma h \Delta A = \sigma h \pi Z^2$$

where h is the thickness and σ is the plastic stress. By analogy with the potential energy in a linear spring system, where

$$\Omega = \frac{1}{2} K Z^2$$

it is seen that the diaphragm system also opposes a restoring force which is proportional to the deflection. The effective value of this "stiffness" is $2\pi\sigma h$. The essential difference between this system and a linear elastic system is that the force opposing the deflection does not return the diaphragm to the neutral position, but merely acts to stop it.

Following the analogy, the diaphragm system may be considered to have a fixed response time which is independent of its deflection amplitude. This is the time required for it to swing out to its maximum deflection and will be referred to as the swing time. If the stiffness and mass are written

$$K_d = 2\pi\sigma h$$

and

$$M_d = \frac{1}{3} \rho h A$$

when the system is regarded as a membrane; then by analogy, the circular natural frequency will be

$$\omega_d = \sqrt{\frac{K}{M}} = \sqrt{\frac{6\pi\sigma}{\rho A}}$$

Then the swing time is

$$t_s = \frac{T_d}{4} = \frac{1}{4 f_d} = \frac{\pi}{2\omega_d} = \frac{\pi}{2\sqrt{\frac{6\pi\sigma}{\rho A}}} = 0.351\sqrt{\frac{\rho A}{\sigma}}$$

For the tank diaphragms, with an area of about 1017 square inches, this gives $t_s = 1.48 \times 10^{-3}$ second. It is significant that this result is independent of the thickness and depends only upon the diameter of the diaphragm.

The compression of the air space produces some restoring force which limits the motion and reduces the swing time. The stiffness of the air space is, however, much less than the effective stiffness of the diaphragm, so that this added stiffness requires only a small correction in most cases.

The diaphragm and the confined air space together thus become a system having a definite time constant, which may be defined in terms of the swing time (13). Under the mechanical filter theory, if the duration of the load is short compared to the swing time, less energy will be absorbed. Stating this in another way, if the swing time can be made longer than the load duration there will be a decrease in the damage done.

The unprotected diaphragms do not offer an opportunity to study the effect of the variation in the swing time. They all have the same diameter, and the variation in thickness does not alter the time constant. Variations in the thickness of the confined air space between two diaphragms should produce small changes in the swing time; the time will be longer for the greater thicknesses. It is also possible to change the stiffness of the air space by compressing the air, or to increase the inertia of the diaphragm by loading it. These experiments have been discussed in various sections of the report.