FINAL REPORT

ON

DIRECT EXPLOSION TEST FOR WELDED ARMOR AND SHIP PLATE— PRIME AND WELDED PLATE TESTS

BY

WILLIAM A. SNELLING

[illegible] Company

Under Navy Contract [illegible]

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

NATIONAL RESEARCH COUNCIL

ADVISORY TO

Bureau of Ships, Navy Department

Under Contract [illegible]

SERIAL NO. SSC-4

COPY NO. 187

AUGUST [illegible]

August 30, 1946

Chief, Bureau of Ships
Navy Department
Washington 25, D. C.

Dear Sir:

Attached is Report Serial No. SSC-4, entitled "Direct Explosion Test for Welded Armor and Ship Plate: Prime and Welded Plate Tests". This report has been submitted by the contractor as the final report on work done on Research Project NRC-25 under Contract No. NObs-31223 between the Bureau of Ships, Navy Department and the Trojan Powder Company.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

Frederick M. Feiker

Frederick M. Feiker
Chairman, Division of Engineering
and Industrial Research

Enclosure

Second Printing
October 1950

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals that were actively associated with this research program. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels."

This is a second printing of the report, one hundred copies having been prepared in the first printing.

Distribution of the second printing is as follows:

Copy No. 101 - Rear Adm. K. K. Cowart, USCG, U. S. Coast Guard Headquarters
Copy No. 102 - Rear Adm. H. C. Shepheard, USCG, U. S. Coast Guard
Copy No. 103 - Rear Adm. Charles D. Wheelock, USN, Bureau of Ships
Copy No. 104 - Col. Werner W. Moore, USA, Office, Chief of Transportation
Copy No. 105 - Captain R. L. Hicks, USN, Maritime Administration
Copy No. 106 - Captain W. N. Mansfield, USNR, Military Sea Transportation Service
Copy No. 107 - Captain H. C. Moore, USCG, U. S. Coast Guard Headquarters
Copy No. 108 - Captain C. M. Tooke, USN, Bureau of Ships
Copy No. 109 - Comdr. H. G. Bowen, USN, Code Re-3, Bureau of Ordnance
Copy No. 110 - Comdr. E. A. Grantham, USN, Military Sea Transportation Service
Copy No. 111 - Comdr. James McIntosh, U. S. Coast Guard
Copy No. 112 - Comdr. W. G. Springer, USN, Bureau of Ships
Copy No. 113 - Constr. Comdr. W. G. Perry, RN, BJSM (Navy Staff)

Copy No. 114 - R. H. Aborn, U. S. Steel Corp. Research Laboratory
Copies 115 and 116 - Air Materiel Command, Wright Field
Copy No. 117 - Clarence Altenburger, Great Lakes Steel Co.
Copy No. 118 - J. G. Althouse, Lukens Steel Company
Copy No. 119 - A. Amerikian, Bureau of Yards and Docks
Copy No. 120 - Raymond Archibald, Public Roads Adm.
Copy No. 121 - T. N. Armstrong, The International Nickel Co.

Copy No. 122 - Wm. M. Baldwin, Jr., Case Institute of Technology
Copy No. 123 - Chas S. Barrett, University of Chicago
Copy No. 124 - L. C. Bibber, Carnegie-Illinois Steel Corp.
Copy No. 125 - R. M. Brick, University of Pennsylvania
Copy No. 126 - British Shipbuilding Res. Assn., Attn: J. C. Asher, Secretary
Copy No. 127 - W. B. Bunn, M. W. Kellogg Co.
Copies 128 thru 152 - Bureau of Ships, Code 692, Attn: C. L. Frear

Copy No. 153 - J. E. Carney, Sun Oil Co.
Copy No. 154 - S. T. Carpenter, Swarthmore College
Copy No. 155 - Perry Cassidy, Babcock and Wilcox Co.
Copy No. 156 - G. E. Claussen, Reid-Avery Co., Inc.
Copy No. 157 - R. W. Clark, General Electric Co.
Copy No. 158 - Morris Cohen, Massachusetts Institute of Technology
Copy No. 159 - J. M. Crowley, Office of Naval Research

Copy No. 160 - L. A. Danse, General Motors Corporation
Copy No. 161 - David Taylor Model Basin, Attn: Library
Copy No. 162 - E. H. Davidson, Carnegie-Illinois Steel Corp.
Copy No. 163 - Bessie Day, U. S. Naval Engineering Experiment Station
Copy No. 164 - J. H. Deppeler, American Soc. of Mechanical Engineers
Copy No. 165 - F. H. Dill, American Bridge Co.
Copy No. 166 - Geo. A. Ellinger, National Bureau of Standards
Copy No. 167 - A. J. Ely, Standard Oil Development Co.
Copy No. 168 - W. J. Eney, Fritz Laboratory, Lehigh University
Copy No. 169 - S. Epstein, Bethlehem Steel Co.

Copy No. 170 - Paul Ffield, Bethlehem Steel Co.
Copy No. 171 - A. E. Flanigan, University of California
Copy No. 172 - W. G. Frederick, Maritime Administration
Copy No. 173 - T. S. Fuller, General Electric Co.

Copy No. 174 - M. Gensamer, Department of Metallurgy, Columbia University
Copy No. 175 - W. P. Gerhart, Bethlehem Steel Co.
Copy No. 176 - B. F. Goud, Detroit Tank Arsenal
Copy No. 177 - N. J. Grant, Massachusetts Institute of Technology
Copy No. 178 - LeVan Griffis, Armour Research Foundation
Copy No. 179 - H. A. Grove, Worth Steel Co.

Copy No. 180 - W. J. Harris, Jr., Naval Research Laboratory
Copy No. 181 - Carl Hartbower, Naval Research Laboratory
Copy No. 182 - M. F. Hawkes, Carnegie Institute of Technology
Copy No. 183 - R. A. Hechtman, University of Washington
Copy No. 184 - K. Heindlhofer, Erie, Pennsylvania
Copy No. 185 - W. F. Hess, Rensselaer Polytechnique Institute
Copy No. 186 - Charles Hoch, Military Sea Transportation Service
Copy No. 187 - E. L. Holladay, U. S. Army
Copy No. 188 - J. H. Holloman, Knolls Laboratory, General Electric Co.
Copy No. 189 - O. J. Horger, Timken Roller Bearing Co.
Copy No. 190 - S. L. Hoyt, Battelle Memorial Institute
Copy No. 191 - L. C. Host, American Bureau of Shipping
Copy No. 192 - J. H. Humberstone, Air Reduction Co., Inc.

Copy No. 193 - Industrial Testing Laboratory, Phila. Naval Shipyard

Copy No. 194 - C. E. Jackson, Union Carbide & Carbon Res. Labs.
Copy No. 195 - L. R. Jackson, Battelle Memorial Institute
Copy No. 196 - T. M. Jackson, Sun Shipbuilding & Drydock Co.
Copy No. 197 - J. W. Jenkins, Bureau of Ships
Copy No. 198 - C. H. Jennings, Westinghouse Electric Corp.
Copy No. 199 - Bruce Johnston, University of Michigan
Copy No. 200 - Jonathan Jones, Bethlehem Steel Co.
Copy No. 201 - S. O. Jones, Newport News Shipbuilding & Drydock Co.

Copy No. 202 - Hubert Kempel, Military Sea Transportation Service
Copy No. 203 - K. V. King, Standard Oil Co. of California
Copy No. 204 - A. B. Kinzel, Union Carbide & Carbon Res. Laboratory
Copy No. 205 - I. R. Kramer, Office of Naval Research
Copy No. 206 - W. J. Krefeld, Columbia University

Copy No. 207 - J. R. Le Cron, Bethlehem Steel Co.
Copy No. 208 - M. Letich, American Bureau of Shipping
Copy No. 209 - M. W. Lightner, Carnegie-Illinois Steel Corp.
Copy No. 210 - R. W. Lilley, Worth Steel Co.
Copy No. 211 - C. E. Loos, Carnegie-Illinois Steel Corp.
Copy No. 212 - C. H. Lorig, Battelle Memorial Institute
Copy No. 213 - J. R. Low, Jr., Knolls Atomic Power Laboratory
Copy No. 214 - E. B. Lutes, Arcrods Corp.

Copy No. 215 - R. C. Madden, Kaiser Co, Inc.
Copy No. 216 - G. M. Magee, Association of American Railroads
Copy No. 217 - W. E. Magee, U. S. Coast Guard
Copy No. 218 - F. L. Maker, California Res. Corp.
Copy No. 219 - A. S. Marthens, Bureau of Ships
Copy No. 220 - O. T. Marzke, Naval Research Laboratory
Copy No. 221 - D. L. Mathias, Metal and Thermit Corp.
Copy No. 222 - C. W. MacGregor, Massachusetts Institute of Technology
Copy No. 223 - J. E. McCambridge, Industrial Testing Laboratory, Phila. Naval SYd.
Copy No. 224 - W. E. McKensie, Metallurgical Branch, Naval Gun Factory
Copy No. 225 - J. E. McNutt, NRC
Copy No. 226 - R. F. Mehl, Carnegie Institute of Technology
Copy No. 227 - C. G. Merker, Carnegie Illinois Steel Co.
Copies 228 thru 232 - Metallurgical Research and Development Co.
Copy No. 233 - W. D. Mitchell, Douglas Aircraft Corp.
Copy No. 234 - N. W. Morgan, U. S. Public Roads Adm.

Copy No. 235 - NACA, Attn: Materials Research Coordination, Navy Department
Copy No. 236 - National Bureau of Standards, Division of Metallurgy
Copy No. 237 - Naval Academy, Post Graduate School
Copy No. 238 - Naval Research Laboratory, Mechanical Division
Copy No. 239 - Naval Research Laboratory, Metallurgical Division
Copy No. 240 - New York Naval Shipyard, Attn: Materials Laboratory
Copy No. 241 - N. M. Newmark, University of Illinois
Copy No. 242 - J. T. Norton, Massachusetts Institute of Technology

Copy No. 243 - E. G. Olds, Carnegie Institute of Technology
Copy No. 244 - E. Orowan, Division of Mechanical Engineering, MIT

Copy No. 245 - H. W. Pierce, N. Y. Shipbuilding Corp.
Copy No. 246 - F. L. Plummer, Hammond Iron Works
Copy No. 247 - N. E. Promisel, Bureau of Aeronautics

Copy No. 248 - Walter Ramberg, National Bureau of Standards
Copy No. 249 - J. F. Randall, Ford Motor Co.
Copy No. 250 - A. J. Raymo, Baldwin Locomotive Co.
Copy No. 251 - W. A. Reich, General Electric Co.
Copy No. 252 - P. J. Rieppel, Battelle Memorial Institute
Copy No. 253 - J. B. Robertson, Jr., U. S. Coast Guard
Copy No. 254 - L. J. Rohl, Carnegie-Illinois Steel Corp.
Copy No. 255 - Bela Ronay, U. S. Naval Engineering Experiment Station
Copy No. 256 - B. E. Rossi, PVRC, 30 Church St., New York 7, N. Y.
Copy No. 257 - V. L. Russo, U. S. Maritime Administration
Copy No. 258 - D. Rosenthal, University of California

Copy No. 259 - George Sachs, Horizons, Inc.
Copy No. 260 - C. M. Schwitter, International Nickel Co.
Copy No. 261 - M. Sedan, Alloy Rods Co.
Copy No. 262 - C. E. Sims, Battelle Memorial Institute
Copy No. 263 - D. C. Smith, Harnischfeger Corp.
Copy No. 264 - Saylor Snyder, Carnegie-Illinois Steel Corp.
Copy No. 265 - C. R. Soderberg, NRC
Copy No. 266 - R. E. Somers, Bethlehem Steel Co.
Copy No. 267 - Alex Spolieensky, Sciaky Bros. Inc.
Copy No. 268 - E. G. Stewart, Standard Oil Co. of N. J.
Copy No. 269 - R. D. Stout, Lehigh University
Copy No. 270 - L. K. Stringham, The Lincoln Electric Co.
Copy No. 271 - R. G. Sturm, Purdue University
Copy No. 272 - C. E. Swartz, Armour Research Foundation
Copy No. 273 - D. Swan, Union Carbide & Carbon Res. Laboratories

Copy No. 274 - R. L. Templin, Aluminum Corp. of America
Copy No. 275 - Testing and Development Division, U. S. Coast Guard
Copy No. 276 - R. D. Thomas, Jr., Arcos Corporation
Copy No. 277 - A. R. Troiano, Case Institute of Technology

Copy No. 278 - U. S. Coast Guard Academy, New London, Conn. Attn: Librarian
Copy No. 279 - U. S. Naval Engineering Experiment Station

Copy No. 280 - H. C. Von Blohm, Bethlehem Steel Co.
Copy No. 281 - R. W. Vanderbeck, Carnegie-Illinois Steel Co.
Copy No. 282 - D. Van Winkle, Carnegie Institute of Technology
Copy No. 283 - C. B. Voldrich, Battelle Memorial Institute

Copy No. 284 - A. T. Waidelich, The Austin Co.
Copy No. 285 - J. E. Walker, Bureau of Ships
Copy No. 286 - W. L. Warner, Watertown Arsenal
Copy No. 287 - T. S. Washburn, Inland Steel Co.
Copy No. 288 - T. T. Watson, Lukens Steel Co.
Copy No. 289 - G. W. Watts, Standard Oil Co. of Indiana
Copy No. 290 - Webb Institute of Naval Architecture
Copy No. 291 - Georges Welter, Ecole Polytechnique Institute
Copy No. 292 - J. B. Wilbur, Massachusetts Institute of Technology
Copy No. 293 - M. L. Williams, National Bureau of Standards
Copy No. 294 - W. H. Wooding, Phila. Naval Shipyard, Industrial Testing Lab.

Copy No. 295 - Carl A. Zapffe, Carl A. Zapffe Laboratory

Copy No. 296 -
Copy No. 297 -
Copy No. 298 -
Copy No. 299 -
Copy No. 300 -

Total Number of Copies - 300

FINAL REPORT

TO THE

NAVY DEPARTMENT

BUREAU OF SHIPS

NObs-31223

DIRECT EXPLOSION TEST FOR WELDED ARMOR AND SHIP PLATE

PRIME AND WELDED PLATE TESTS

Report Prepared by

William A. Snelling

X

Trojan Powder Company

Allentown, Pa.

January, 1946

SUMMARY

Direct Explosion Test for Prime and Welded Steel Plate

1. The direct explosion test has been reduced to practice and its ability to determine the relative resistance to multi-axial shock loading of prime or welded steel plates with reproducible accuracy has been demonstrated.

(a) Tests to compare butt-welded steel plates in the as-welded condition with similar welded specimens, which had been stress relieved using the low temperature stress relief method, have been performed.

(b) Tests to compare butt-welded steel plates in the as-welded condition with similar welded specimens some of which were flame stress relieved and some of which were furnace stress relieved have been performed.

2. An investigation was conducted to ascertain whether or not it was possible to reproduce by shock loading in 0.025" thick specially-treated material, the extent and distribution of deformation produced in 0.5" thick medium steel plate subjected to the explosion test.

Final Report

Navy Department Bureau of Ships NObs-31223

TABLE OF CONTENTS

Abstract

The direct explosion test has been utilized to determine the relative resistance of welded and unwelded steel specimens to shock loading. The tests were conducted using a special explosive which is detonated in direct contact with the specimen under controlled conditions. Repetitive tests have demonstrated the excellent reproducibility of the test.

DIRECT EXPLOSION TEST FOR PRIME AND WELDED PLATE

I. Introduction.

A. During the period covered by this report, the direct explosion test for prime and welded plate has been reduced to practice, i.e., specimens have been submitted for testing and the results of such tests have been used as an index of structural performance of various specimens subjected to severe loading conditions.

B. Possible methods of shock testing 0.025" specially-treated steel sheet by means of explosives were studied.

A discussion of each of the studies outlined above follows the details of the experimental equipment and explosive characteristics below:

Original tests indicated that a firm base on which the specimen and related supports could be placed for testing was necessary, and that certain inaccuracies could thereby be eliminated. The base shown in Figure 1 (Photograph B-63) has proven satisfactory and consists of an eight foot square block of reinforced concrete fifteen inches thick and which rests on a bed of well-compacted cinders. Two pieces of steel, the lower 3" thick and the upper 1" thick, weigh a total of approximately 2,500 lbs. and are placed on top of the concrete. The top piece of steel is easily replaced if it becomes damaged.

Original tests indicated that both the physical shape of the explosive charge and the type of explosive charge must be controlled. A cylindrical pellet was found to be desirable and a device known as a Standard Density Apparatus, developed by the Trojan Powder Company a number of years ago, was found to be readily adaptable to the making of suitable pellets with the testing explosives used.

Several modifications of the Standard Density Apparatus have been made, one of which is shown in Fugures 2 and 3. These figures illustrate the equipment specifically adapted to make pellets 75 mm in diameter. With this apparatus the density of the explosive charge can be controlled within certain limits at will, and densities have been consistently reproduced with a variation of less than 1%. Figure 2 shows the apparatus completely assembled and ready for use, while Figure 3 shows the apparatus disassembled.

The type of explosive required has been found to be influenced by the particular steel specimens being investigated, so that a number of specialized explosives have been formulated to meet the various needs, and in all cases the characteristics of the testing explosives are measured by subjecting them to a number of tests, the most important of which are the ballistic pendulum test which is an index of the gas volume, the rate of detonation test which measures the speed of the detonating wave, and the standard density test which measures the density under standardized conditions.

After the physical shape of the charge and the type of explosive had been decided upon, an initiator was designed so that the charge could be used with greatest effectiveness (Figure 4). This initiator is placed on top of each charge of explosive and consists of a ring about 1-1/2" in diameter of Ensign-Bickford Primacord and a piece extending across the center of the ring, both of which are firmly attached to a small wooden block. One end of each of two lengths of Primacord is bent in the form of a semicircle to make the ring, and the opposite end of one is twisted several times around the extending portion of the other. The detonator is attached to this upwardly extending part.

When the detonator is fired, the length of Primacord is caused to detonate which in turn detonates the explosive charge. The flat ring is placed so that its entire circumference makes contact with the top of the explosive charge. Since the detonation of the charge takes place around its circumference instead of from one spot which would be the case when a detonator alone is used the detonation wave travels practically in a straight downward direction.

The quantity of explosive contained in this initiator is approximately 2.89 grams, and the amount of explosive actually touching the explosive charge is only about 1.18 grams.

On the basis of the results obtained with this initiator, it appears to be a definite improvement over the use of a detonator alone.

It is of utmost importance to have thoroughly in mind the fundamental characteristics of an explosive in order to understand or control its effects. These fundamentals were used as a starting point for the formulation of a special testing explosive to be used in this research project. From past experience the effects of explosives have been conveniently classified into brisant effects and gas volume effects, the inter-relationship of which can cause any of the infinite number of variations in the types of shock produced by explosive action. It is entirely true, however, that this distinction is not entirely a physical one, and that there is a little overlapping in the two types of effects.

A highly brisant explosive (that is, one with a rapid rate of detonation) will produce a very shattering and destructive blow which is many times charaterized by a spall or a hole when an armor plate is subjected to such a shock. In contrast, a "slow" explosive or one with low brisance (low rate of detonation) tends to move or deform material in its vicinity. A dish or cup-shaped indentation is likely to be the result of the application of such an explosive force against steel plate, depending on how slow the rate of detonation is, and the type of steel.

A very good analogy of the rate of detonation and gas volume of an explosive can be found in ballistics in the speed and mass of the projectile when in flight. The speed of the projectile can be likened to the rate of detonation of an explosive, while the mass of the projectile can be likened to the gas volume. It is known that a projectile must have a certain mass in combination with its velocity in order to penetrate a plate, and similarly an explosive must have a sufficiently high gas volume in order to have a sufficient force with which to perform the particular task desired. Just as the weight and speed of a projectile can be varied within wide limits in accordance with specific requirements, so can an explosive be formulated to have almost any combination of rate of detonation and gas volume within reasonable limits that are desired.

From previous experience it was decided that in order to produce more "dishing" and less "spalling" in the specimens tested by the direct application of an explosive shock, the explosive to be developed would have to have a comparatively low rate of detonation and sufficient gas volume.

A number of experimental explosives were formulated and tested by methods then in use which included rate of detonation tests, standard density tests, gas volume tests, and small lead block tests, and also by actual tests on steel plates. Several of the explosives made produced satisfactory hull plate defromation, and finally an experimental explosive designated as NS-D was adopted as being the most promising. This explosive contains trinitrotoluene as its basic explosive ingredient, with ammonium nitrate and sodium nitrate as cooperating oxidising salts as well as several other chemical components. Not only are the proportions important, but it was learned that the particle size and the intimacy of mixture are significant factors in obtaining reproducible results.

NS-D explosive is a dry, pulverulent powder with a density of about 1.16 (water = 1.00), a rate of detonation of approximately 2200 meters per second, and a gas volume of 10.5 (TNT standard = 10.0).

Additional details of the testing procedure, experimental equipment, and explosives used in these tests are presented in a series of earlier reports. (Final Report - Part I, OSRD No. 4655, Serial No. M-446 dated 23 January 1945; Final Report - Part II, OSRD No. 6382, Serial No. M-622 dated 5 December 1945).

II. Results and Discussion.

A. Tests Comparing As-Welded with Stress Relieved Butt-Welded Ship Steel Specimens.

A group of twenty 18" x 18" x 3/4" butt-welded specimens, ten of which were in the as-welded condition, and ten of which were stress relieved, were tested using the direct explosion test to determine whether stress relieving affected the resistance to shock loading. The stress relieved specimens were prepared using the low temperature method of stress relief which involves the heating of the metal on each side of the weld and parallel thereto (by a moving flame to a temperature not over 400°F), while at the same time cooling the weld itself with a stream of water. The temperature differential causes plastic flow in the weld thereby reducing the residual welding stress.

These tests were requested by the U. S. Coast Guard. No unwelded specimens were furnished.

The steel used to prepare these specimens was of the rimmed type and was procured from the Worth Steel Co. The chemical analyses and mechanical properties of this steel are listed in Table I:

TABLE I

Melt No.	Slab No.	Chemical Analysis in % C	Mn	P	S
6-F3983	3	0.18	0.43	0.021	0.025

Test Piece Thickness	Test Piece Sec. Area	Yield Point Lbs. per Sq. In.	Tensile Strength Lbs. per Square Inch	% Elongation in 8"
0.738"	1.122 sq. inches	37,700	59,500	32.7

Each specimen was prepared by joining two 9" x 18" x 3/4" pieces together using E 6010 electrodes with a double-V, 60° included angle, butt weld consisting of eight passes, after which the weld reinforcement was removed on one side of the plate. The weld reinforcement within 1-1/4" of each edge of the plate was removed on the opposite side, so that the plates could be supported evenly during the test.

Figure 5 shows a typical plot of the longitudinal stress pattern of the as-welded specimens. Figure 6 shows a plot of the longitudinal stress pattern in a typical stress relieved plate, and also gives as a comparison the average stress pattern shown in Figure 5. In addition, Figure 6 indicates the temperature attained at various points during the stress relieving process.

The plates were stored prior to testing in an insulated cabinet with the temperature maintained at 70°F ± 1/2° (21 ± °C).

The powder charge consisted of NS-D explosive (Lot 556 B), and was packed by means of a Standard Density Apparatus in 75 mm diameter paper cartons. In all tests except those on Place 1C, Specimen 1 and Plate 1C, Specimen 2, the charge was prepared in two increments. In the above-mentioned two tests, however, the charge was prepared in three increments.

In general, each specimen was supported by centering it on a symmetrical "pin wheel type" support as shown in Figure 1, and the explosive charge was centered on the weld at the center of the plate and confined in an 8-1/2" diameter x 12" high kraft carton filled with approximately 35 lbs. of 20-30 mesh Ottawa sand, and was detonated by means of a #6 fuse-type blasting cap attached to a Primacord initiator which was in juxtaposition with the top of the explosive column, all of which is in conformity with the usual established testing procedure. In Figure 1, a plate of glass is used instead of a steel plate to show the manner of support. The outer confining container is cut away to show the Ottawa sand and the explosive cylinder. The Primacord initiator and the fuse are also shown. This symmetrical method of support simulates the four-sided support that a section of a plate receives from the plate surrounding it.

In a few specific instances some parts of this general procedure were departed from, which are as follows:

In all tests except those on Plate 4C, Specimen 3 and Plate 4C, Specimen 4, the distance between the supports was 16" measuring from the inside of a bar to the one parallel to it. In the case of those two specimens, the distance between the supports was 10" and the charge was not centered on the plate and was placed on the parent metal.

Specific data for each test is as follows:

TABLE II

Test No.	Specimen Number	Total Charge Wt. in Grams	Grams per Increment	No. of Increments	Results
			AS WELDED		
NS-187	PL1C spec. 4	180	90	2	No failure. 57 mm dish parallel to weld. 58 mm dish perpendicular to weld.
NS-188	PL1C spec. 5	200	100	2	No failure. 61 mm dish parallel to weld. 62 mm dish perpendicualr to weld.
NS-192	PL3C spec. 1	200	100	2	No failure, 59 mm dish parallel to weld. 61 mm dish perpendicular to weld.
NS-200	PL3C spec. 5	205	102, 103	2	Broke in 4 pieces.
NS-190	PL3C spec. 3	210	105	2	Broke in 3 pieces.
NS-194	PL3C spec. 2	210	105	2	Broke in 4 pieces.
NS-189	PL3C spec. 4	220	110	2	Broke in 3 pieces
NS-186	PL1C spec. 3	230	115	2	Broke in 4 or more pieces. 1 or more not recovered.
NS-185	PL1C spec. 2	280	94, 92, 94	3	Broke in 3 pieces.
NS-184	PL1C spec. 1	330	110	3	Broke in 5 pieces.
			STRESS RELIEVED (using the low temperature method of stress relief).		
NS-191	PL2C spec. 4	210	105	2	No failure. 63-1/2 mm dish parallel to weld. 65 mm dish perpendicular to weld.
NS-193	PL2C spec. 3	230	115	2	No failure. 67 mm dish parallel to weld. 70 mm dish perpendicular to weld.
NS-197	PL2C spec. 5	230	115	2	No failure. 65 mm dish parallel to weld. 67 mm dish perpendicular to weld.
NS-201	PL4C spec. 5	232-1/2	116.25	2	Broke in 5 pieces.
NS-199	PL4C spec. 2	235	117,118	2	Broke in 4 pieces.

TABLE II (cont'd)

Test No.	Specimen Number	Total Charge Wt. in Grams	Grams per Increment	No. of Increments	Results
NS-196	PL2C spec. 2	240	120	2	Broke in 5 pieces.
NS-198	PL4C spec. 1	250	125	2	Broke in 4 pieces.
NS-195	PL2C spec. 1	250	125	2	Broke in 4 pieces.
CHARGE NOT ON WELD					
NS-202	PL4C spec. 3	230	115	2	No failure.
NS-203	PL4C spec. 4	240	120	2	Broke in 2 pieces. Considerable petalling.

All PL1C and PL3C plates were as-welded and all PL2C and PL4C plates were flame stress relieved.

It can be seen in Table II that all charges of 205 grams or more caused failure in the as-welded plates, whereas all charges of 200 grams or less did not cause failure in the as-welded plates. The as-welded plates are considered to have a breaking strength range of from 200 to 210 grams which has been consistently established with a double check both at 200 grams and at 210 grams.

All charges of 232-1/2 grams or more caused failure in the stress relieved plates, whereas all charges of 230 grams or less did not cause failure in the stress relieved plates. The stress relieved plates are considered to have a breaking strength range of from 230 to 240 grams, which has been consistently established with a double check at both 230 grams and 240 grams.

The term "breaking strength range" is used in this report to indicate the maximum charge at which no failure occurred and the minimum charge at which failure occurred. In some instances, a double check is used to bound the breaking strength range.

Using the above procedure, the stress relieved plates require 30 grams more explosive charge to cause failure than did the as-welded plates.

It is interesting to note that stress relieved plate PL4C, specimen 3 which was tested with a 230 gram charge did not fail, and that stress relieved plate PL4C, specimen 4 which was tested with a 240 gram charge did fail in view of the fact that both of these plates were tested following a different procedure from that followed for NS-184 to NS-201. NS-202 (Plate PL4C, specimen 3) and 203 (Plate PL4C, specimen 4) were tested while the specimen was supported on the four sets of bars placed in a pin-wheel fashion with each set of parallel bars being 10" (instead of 16") apart.. The specimen was placed on the support bars so that each side of one corner of the specimen was supported by a 1" portion of each of the two support bars, over which it rested. The other two supports were completely covered by the specimen. The explosive charge was centered on that portion of the plate supported by the bars, and therefore, its center was 6" from each edge of the corner above mentioned, and consequently was not over or touching the weld.

Note: Some of the specimens exhibited a slight amount of warping due to welding and therefore did not rest absolutely flat on the support bars.

B. Tests Comparing As-Welded with Several Types of Stress Relieved Butt-Welded Steel Specimens.

The specimens discussed in this sedtion are not comparable with those discussed in the previous section because of the difference in the stress relieving practice, and in view of the different type of steel used. The specimen size is also different.

A group of eighteen 12" x 12" x 3/4" butt-welded specimens were tested to determine their relative resistance to shock loading as obtained by the direct explosion test. Six were in the as-welded condition, six were furnace stress relieved at 1150°F for one hour, and six were torch stress relieved by passing a multiple tip torch progressively over the weld bead on one side of the plate only (side on which weld reinforcement had been machined off). The weld metal reached a temperature of 900°F on the side opposite to the flame and this temperature was maintained for 10 minutes. A fully killed, normalized steel was used to prepare these specimens. This steel was furnished from Lukens Steel Co., Heat No. 20340, Slab No. 6, Plate No. 142, and had the following chemical analysis:

TABLE III

Carbon	Manganese	Phosphorous	Sulfur	Silicon	Copper
0.18	0.55	0.015	0.028	0.23	0.20

Each specimen was prepared by welding two 6" x 12" x 3/4" plates together using Type E 6010 electrodes in the downhand position with a double-V, 60° included angle, butt weld consisting of eight passes, after which the weld reinforcement was removed on one side of the plate, and that part of the weld reinforcement within 1-1/4" of each edge of the opposite side of the plate was also removed. The direction of rolling was to right angles to the weld axis.

The plates were stored in an insulated cabinet with the temperature maintained at 70°F ± 1/2° (21 ± °C).

The powder charge consisted of NS-D explosive (Lot 556 B, the same explosive used to test the twenty specimens discussed in the preceding section of this report), and was packed by means of a Standard Density Apparatus in 75 mm diameter paper cartons in two increments, and was confined in an 8-1/2" diameter x 12" high kraft carton filled with approximately 35 lbs. of 20-30 mesh Ottawa sand, and was detonated by means of a fuse-type detonator attached to a Primacord booster placed in juxtaposition with the top of the explosive charge in the usual manner. The weight of charge was the only controllable factor varied for each plate.

The results of the tests follow:

TABLE IV

Test No.	Specimen Number	Total Charge Wt. in Grams	Grams per Increment	Results
			AS WELDED	
NS-207	1	180	90	47 mm dish parallel to the weld. 53mm dish perpendicular to the weld. Plate 7/8" longer perpendicular to weld than parallel to it. No failure.

TABLE IV (cont'd)

Test No.	Specimen Number	Total Charge Wt. in Grams	Grams per Increment	Results
			AS WELDED (cont'd)	
NS-210	2	190	95	50 mm dish parallel to weld. 53 mm dish perpendicular to weld. Plate 5/8" longer perpendicular to weld than parallel to it. No failure.
NS-216	5	190	95	51 mm dish parappel to weld. 55 mm dish perpendicular to weld. Plate 1" longer perpendicular to weld than parallel to it. No failure.
NS-204	4	200	100	Plate failed by transverse cracking. Plate remained in one piece. Light could be seen through places of failure.
NS-213	3	200	100	Plate failed by transverse cracking. Plate remained in one piece. Light could be seen through places of failure.
			TORCH STRESS RELIEVED	
NS-209	17	180	90	50 mm dish parallel to weld. 52 mm dish perpendicular to weld. No failure.
NS-212	14	190	95	52 mm dish parallel to weld. 51 mm dish perpendicular to weld. No failure.
NS-218	16	190	95	50 mm dish parallel to weld. 55 mm dish perpendicular to weld. Plate 3/4" longer perpendicular to weld than parallel to it. No failure.
NS-206	13	200	100	Broke in 3 pieces with failure transverse to weld.
NS-215	18	200	100	Broke in 2 pieces with failure transverse to weld.
			FURNACE STRESS RELIEVED	
NS-205	7	200	100	51 mm dish parallel to weld. 57 mm dish perpendicular to weld. Plate 7/8" longer peprpendicular to weld than parallel to it. No failure.

TABLE IV (cont'd)

Test No.	Specimen Number	Total Charge Wt. in Grams	Grams per Increment	Results
		FURNACE STRESS RELIEVED (cont'd)		
NS-208	9	220	110	57 mm dish parallel to weld 58 mm dish perpendicular to weld. No failure.
NS-211	10	230	115	56 mm dish parallel to weld. 60 mm dish perpendicular to weld No failure.
NS-214	11	240	120	58 mm dish parallel to weld. 58 mm dish perpendicular to weld. No failure.
NS-217	12	250	125	57 mm dish parallel to weld. 61 mm dish perpendicular to weld. Plate 1" longer perpendicular to weld than parallel to it. No. failure.
NS-219	8	260	130	55 mm dish parallel to weld. 62 mm dish perpendicular to weld. Plate 1-1/4" longer perpendicular to weld than parallel to it. No. failure.

It can be seen in Table IV that the breaking strength range for the as-welded plates was between 190 g and 200 g, such results having been consistently established by performing two tests at both 190 g and 200 g and obtaining similar results.

The breaking strength range for the furnace stress relieved plates is above 260 g since no failure occurred in this series at that charge or at a lesser charge.

The breaking strength range for the torch stress relieved plates was between 190 g and 200 g, such results having been consistently established by performing two tests at both 190 and 200 g and obtaining similar results.

Tests made on silicon killed, normalized steel, Heat 20340, utilizing a different lot of NS-D explosive gives a rough comparison of the difference between prime (unwelded) plate and the various welded specimens which were prepared from the same steel and the results of which are cited above. The breaking strength range was between 400 and 420 g. A dish of 75 mm was the maximum obtained without accompanying plate failure.

Figure 7 (Photograph B-53) is included to show a 1" welded plate with a typical transverse failure. The tests on this series are covered in OSRD Report No. 6382, Serial No. M-622, dated 5 December, 1945. This specimen was made from high tensile steel welded with E 6010 electrodes.

Note: The differences noted between the measurements of the depth of the dish parallel to the weld and perpendicular to the weld as stated in the results column is due largely to the fact that the plates were not square, and that in addition, the specimens were not 12" on each side. The depth of dish figures are, therefore, given in the thought that they may be of some help in analysing the results qualitatively.

C. Testing of 0.025" Thick Specially-Treated Steel Plate Utilizing Explosives.

The Pennsylvania State College under NDRC Project NRC-96 and now under Navy Contract NObs-31217, has been engaged in developing a thin steel sheet for model studies which will exhibit the same behavior as 1/2" ship plate when subjected to rapid biaxial loading in an underwater explosion. A number of different types of thin sheet steel were developed, which when tested statically in a hydraulic system were found to exhibit several times the ductility of a 5' x 5' x 1/2" plate tested by detonating a charge of explosive in contact with the geometrical center of the under side of the plate which was in the water while the opposite side was in the air.

It was thought that the increased ductility obtained might have been the result of either the size effect, or the great difference in the speed of testing. It was, therefore, desirable to test the thin specimens utilizing a charge of explosive in the effort to obtain an answer to that question. Consequently, preliminary tests were undertaken which are described below:

Circular specimens of the special experimental steel sheet, 3" in diameter x 0.025" thick were centered on the top surface of a cylindrical brass support having a 2-1/2" diameter hole bored concentric with the outer wall of the support, and were tested using a very small explosive charge.

The specimen was not clamped to the brass support, but was held in place by the weight of a plaster of paris disc approximately 4" in diameter and 1" thick through the center of which a small hole had been drilled parallel to its axis. Any one of the standard test detonators which are prepared with various weights of charge accurately weighed and contained in a small copper capsule and numbered in steps of one-half from #1/2 to #4, and in steps of one from #4 to #8 would fit snugly in the hole. The lowest numbered detonator has the smallest charge which is less than 1/4 gram.

The test was performed by inserting the fuse-type test detonator in the hole in the plaster of paris disc which was placed on the top of the steel test specimen so that the detonator rested on the center thereof. The specimen was in turn centered over the hole in the brass support. No auxiliary charge was used, since it was found that test detonators between numbers 1/2 and 2 supplied the desired degree of explosive force. During the explosion the plaster of paris disc provided confinement.

The few tests run indicate that specimens prepared by different heat treatment methods can be differentiated by this test. One of the specimens tested had been marked with a grid on the side opposite that on which the explosive charge was placed, and subsequent to testing the deformation of the specimen (the maximum obtainable without failure) at various points was plotted. Not as much ductility is shown when an 0.025" thick specimen is tested with a high rate of shock loading as when it is tested statically in a hydraulic system, indicating a speed effect.

A testing apparatus was designed, the drawing of which is shown in Figure 8, so that the circular specimens could be tested in a hydraulic medium utilizing the shock produced by the detonation of a charge of explosive.

The charge is placed in the center of the large part of the fluid chamber and is entirely surrounded by the fluid. All air is displaced by the fluid. After the specimen and the charge are in place, the apparatus is sealed and the charge detonated. The shock wave travels through the fluid in the small channel to the specimen, one side of which is exposed to the fluid. The deformation obtainable may be varied by changing the weight of the charge, and by other methods not investigated. This work was in progress when the contract terminated.

III. Conclusions.

1. Tests have shown that the static detonation of an explosive charge under controlled conditions in direct contact with welded and unwelded steel specimens provides a convenient and reproducible method for determining the relative resistance to failure under conditions of multi-axial shock loading.

2. Using the direct explosion test, it is possible to determine the effects of stress relieving, pre-heating, electrode composition, and other changes in welding procedure on performance.

3. It has been determined using the direct explosion test that a special low temperature stress relieving process in which plastic flow is produced in the weld by thermal loading does not adversely affect the behavior of welded plates when subjected to severe conditions of loading. Actual test data show a slight improvement in performance for the specimens prepared using the low temperature stress relief process.

4. Tests conducted on welded plates furnace stress relieved at 1150°F showed improved shock resistance over corresponding as-welded specimens.

5. It is possible using a special technique to explosively test sheet specimens 0.025" thick. Tests made on specially-treated steel sheet in this thickness have exhibited reduced ductility when compared with corresponding static bulge test specimens. These results indicate that ductilities exhibited in bulge tests in this thickness range are considerably affected by the speed of testing. (Strain distribution will be included in a report to be prepared under Contract NObs-31217).

Figure 1. Base Plate and Test Set-up

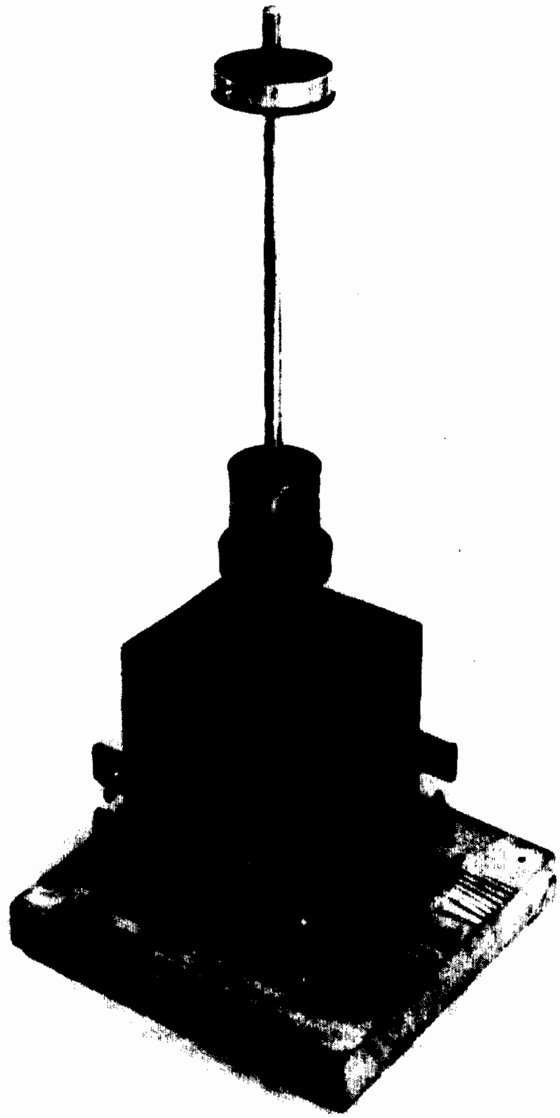

Figure 2

75 mm. Standard Density Apparatus Assembled

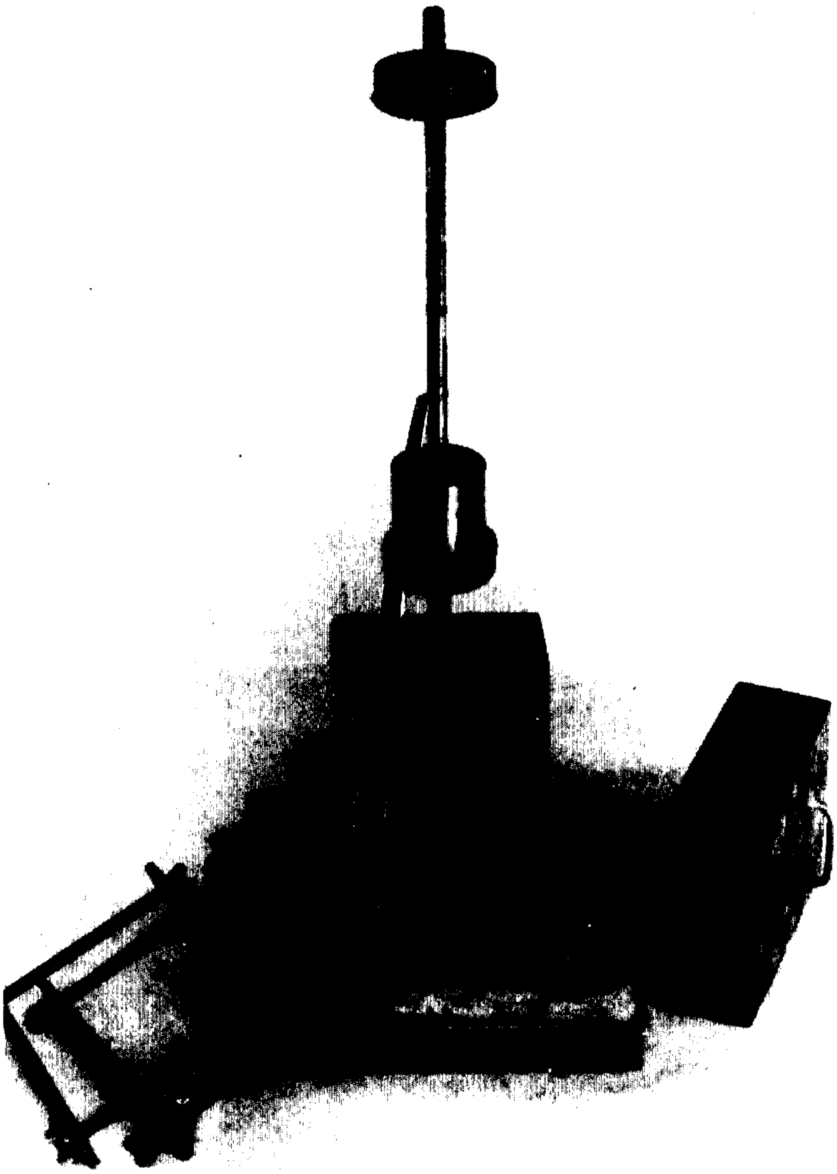

Figure 3

75 mm. Standard Density Apparatus Disassembled

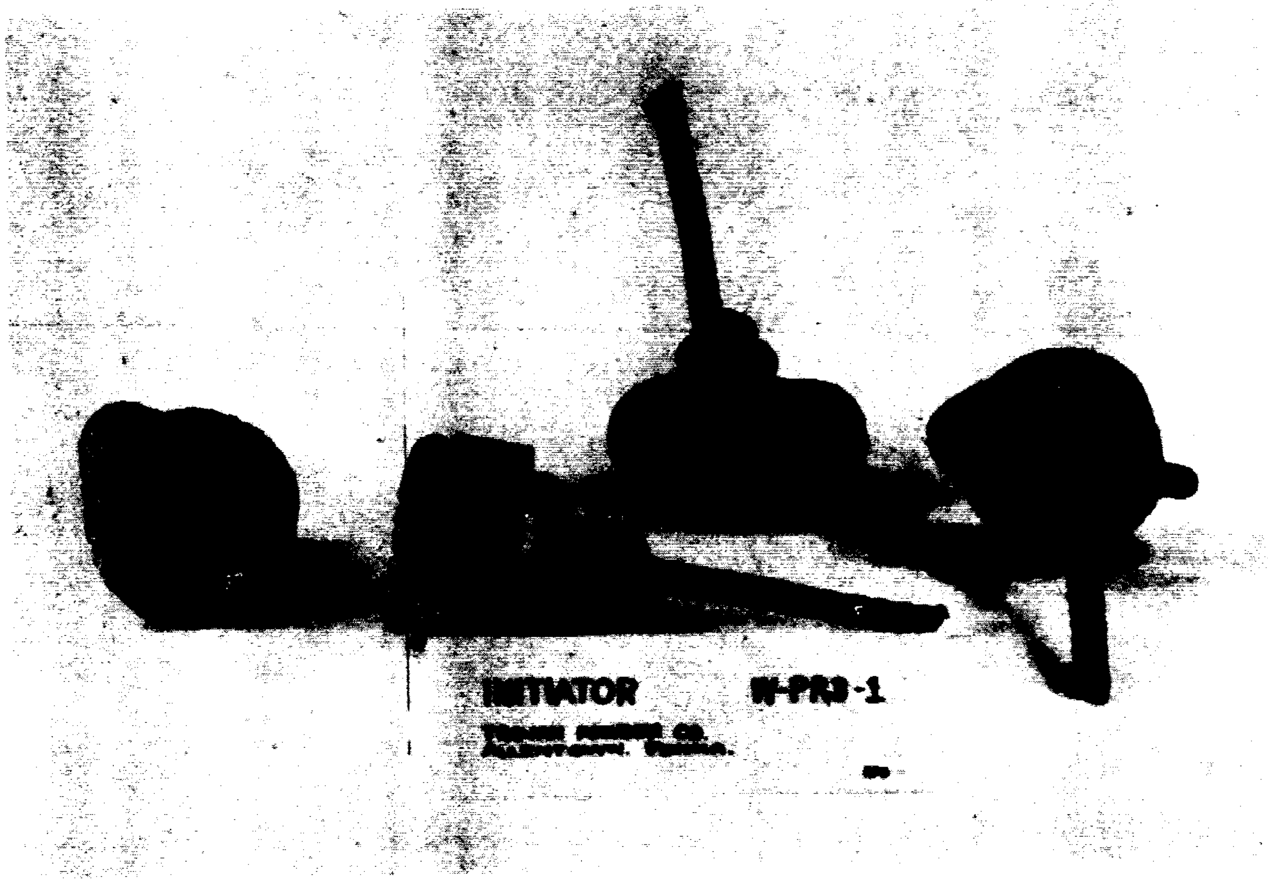

Figure 4. Initiating Device

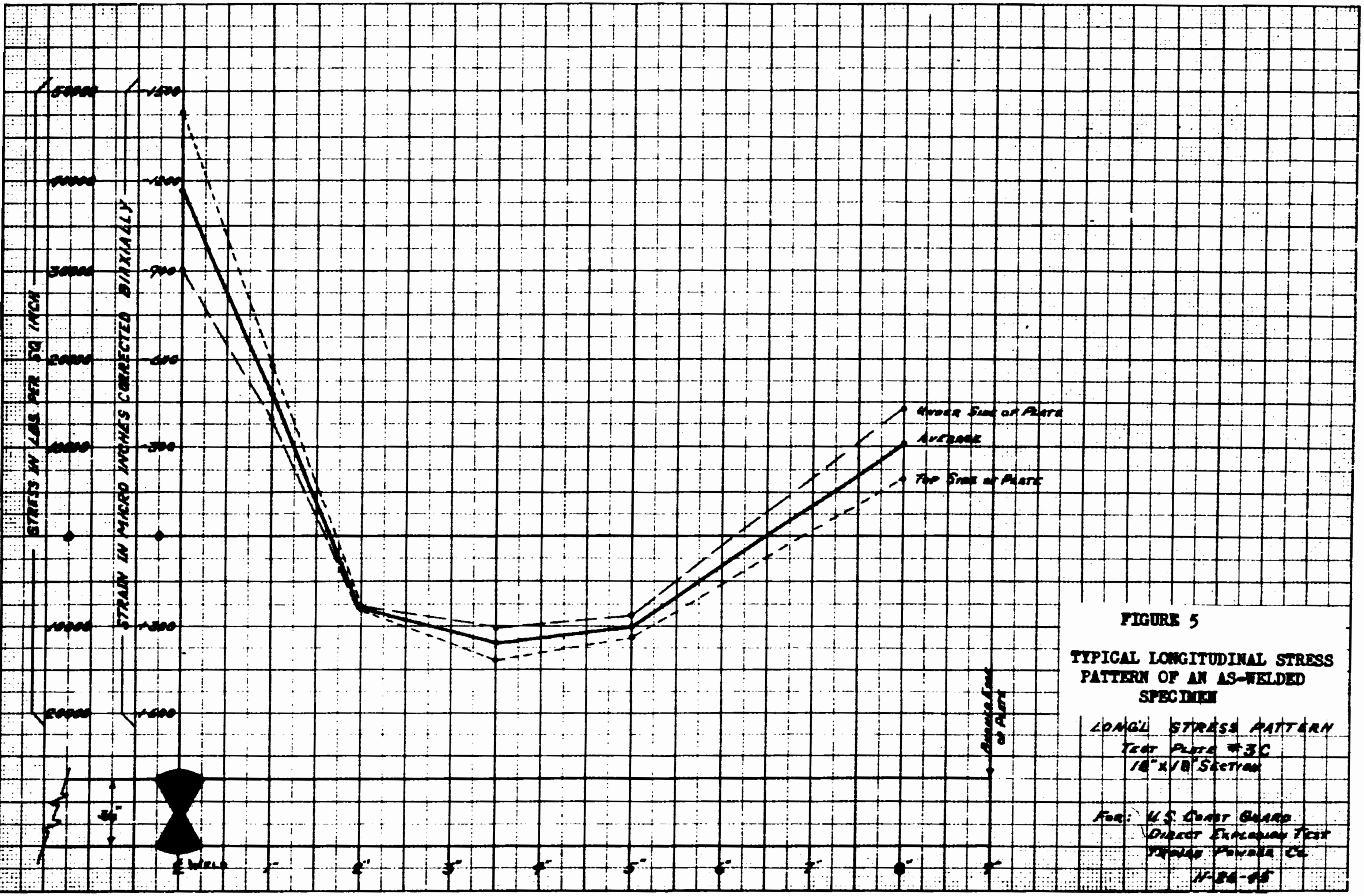

FIGURE 5

TYPICAL LONGITUDINAL STRESS PATTERN OF AN AS-WELDED SPECIMEN

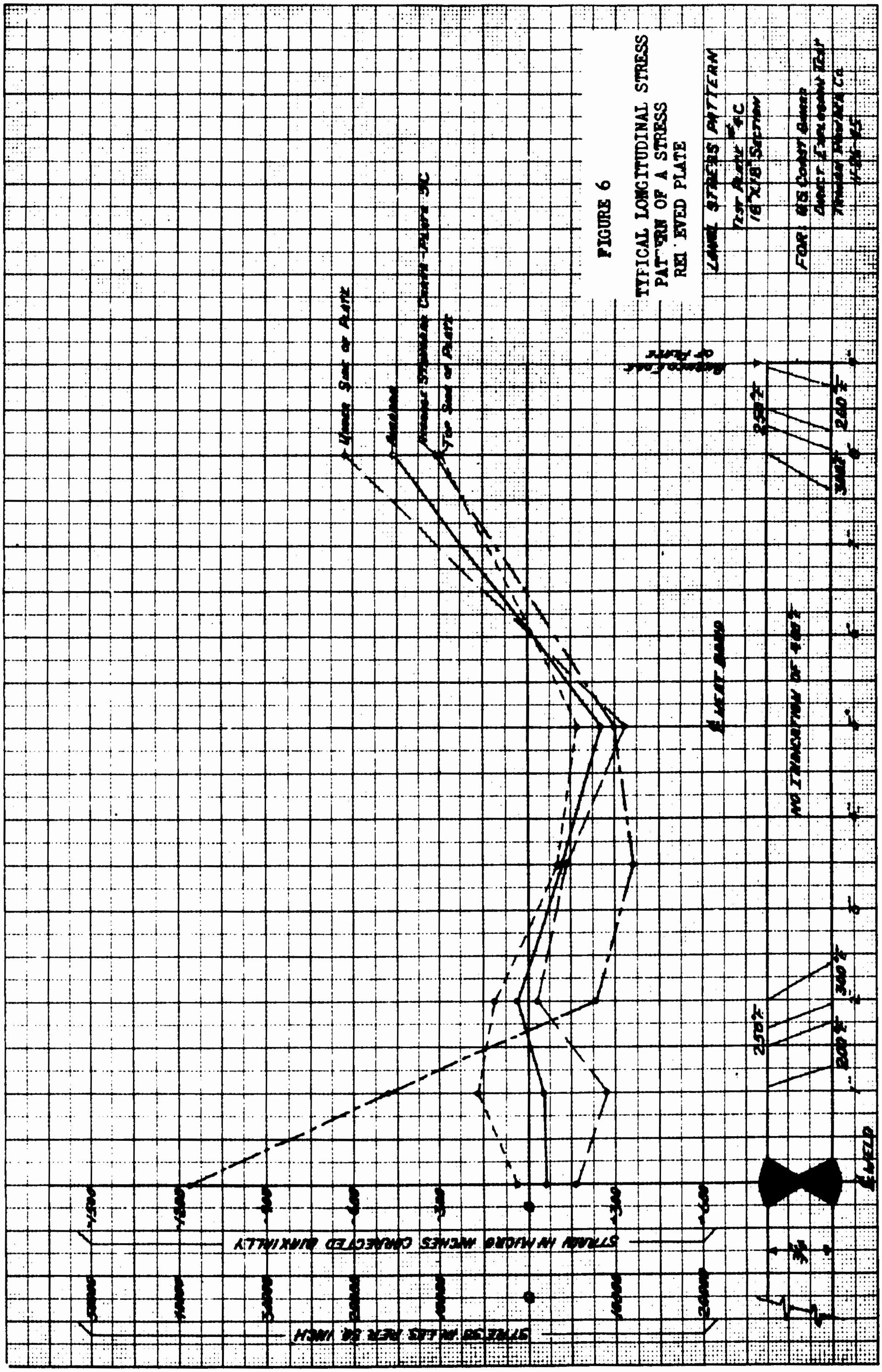

FIGURE 6

TYFICAL LONGITUDINAL STRESS PAT"RN OF A STRESS REI EVED PLATE

Figure 7

H.T.S. Plate Showing Typical Transverse Weld Failure

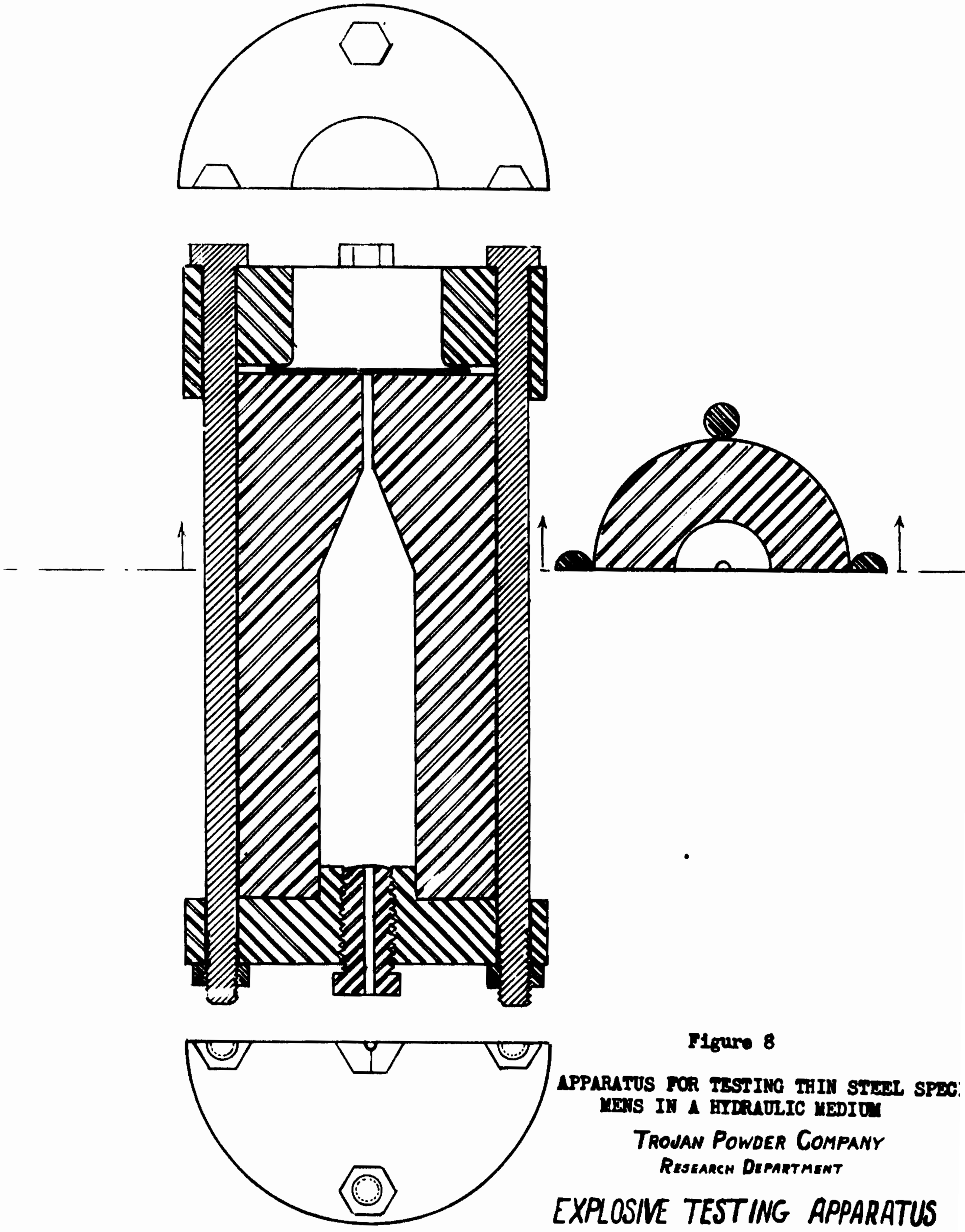

Figure 8

APPARATUS FOR TESTING THIN STEEL SPECIMENS IN A HYDRAULIC MEDIUM

TROJAN POWDER COMPANY
RESEARCH DEPARTMENT

EXPLOSIVE TESTING APPARATUS

EMPLOYING A LIQUID MEDIUM
FOR TRANSMISSION OF PRESSURE

SCALE 1/2" = 1"

W.A.S.-W.H.P. 26 Nov. 1945