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EXPLOSIVE TESTING OF WELDS

CONTRACT DAAE07-85-C-R157

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The objective of this program was the development of an alternative test method for testing sample weld plates for weld procedure qualification, using shaped charges instead of the Ballistic Weld Test Procedure of MIL-STD-1941(MR). The proposed method would have reduced turnaround time and cost by allowing locally conducted testing, achieving weld test results in a much shorter time. Charge placement would have been accurately controlled, eliminating the need for duplicate samples because impact locations were unacceptable.

Testing to date indicates that the charge sizes required to form an impression similar to the ballistic projectile would result in too much noise and ground vibration for local use. Also, the measured weld damage and impression depth do not appear to be consistent with charge size.

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PREFACE

This report discusses a program to develop an alternative test method for testing sample weld plates for weld procedure qualification, using shaped charges instead of the Ballistic Weld Test Procedure of MIL-STD-1941(MR). The program was conducted under the auspices of the U.S. Army Tank-Automotive Command.

The report discusses the various tests conducted and conclusions reached. It also recommends future actions.

The author thanks J. Wayne Schroeder, whose pioneering work in explosive forming is the basis for this work. He is grateful for the help of Explosive Fabricators, Louisville, Colorado, in conducting the tests.

The author appreciates the assistance of the TACOM editing staff, in particular Julie McCutcheon of the Research, Development and Engineering Center Technical Editorial Office.

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1.0. INTRODUCTION

This final technical report was prepared by Foster Wheeler Development Corporation (FWDC) for the U.S. Army Tank-Automotive Command (TACOM) under Contract DAAE07-85-C-R157. It describes the design procedures, testing, and results obtained in developing an alternative to the present Ballistic Weld Test Procedure of MIL-STD-1941(MR)[1]. Currently, welds and weld procedures used on military vehicle armor are tested by transporting weld test plates to a military proving ground. There a projectile is fired at a particular velocity at the welded test plate. Weld procedure acceptability is based upon an examination of the plate to determine impact position, weld crack length, and plate cracking tendency. This process can take from 3 to 6 months, depending on the priority and scheduling at the military proving ground. A misdirected shot at the test plate can cause a "no test" condition, requiring a second sample. These delays can add to the cost and time needed to qualify newly developed weld procedures.

The objective of this program was to develop a shaped explosive charge, with or without a projectile, to simulate the impression developed in the weld test plate by the impacting projectile. A shaped charge is an explosive device--in some cases enclosed in a shaped container--which tends to focus a part of its energy into an intense forward "jet" that is preferentially directed. In some instances part of the shaped charge containment vessel is used for the jet mass, which transfers the charge energy to the final receptor in what is called the "charge jet." The shaped charge concept would allow local testing, reducing transportation time and cost, minimizing misdirected "no test" shots, and permitting immediate analysis of weld acceptability. Additionally, rapid adjustments could be made in the welding parameters, aiding the more extensive investigation of a variety of conditions in a short period of time. More timely use of the advanced weld procedures would lower vehicle fabrication cost and expedite design and fabrication of advanced vehicles.

To maintain the present pass-fail criteria and its vast data bank of information instead of developing a new acceptance criteria, projectile impact impression, shape, and depth were chosen as the damage criteria to be simulated by the alternative test procedure.

2.0. OBJECTIVE

The primary program goal was to develop and test a shaped charge that could be used locally to develop damage in a 1.5-in.-thick armor plate weld sample similar to that produced by a projectile impact [75 mm at 1200 ±25 feet per second (ft/s)], as required in MIL-STD-1941(MR) for weld procedure qualification.

3.0. CONCLUSIONS

With or without projectiles, the shaped charges that were tested did not produce a combined impression shape and depth and crack damage similar to that produced by a ballistic projectile impacting upon a 1.5-in.-thick armor welded plate. The size of charge estimated to produce such an impression and depth would be too great for local use because of excessive noise and ground vibration. Commercial facilities are available for detonating such a large charge, but the plates would have to be shipped to the site on a scheduled basis, as is done presently.

A number of shaped charge designs were tried, including simple cylindrical, cylindrical with both shaped and cylindrical cavities, layered cylindrical projectiles, and solid shaped projectiles. The selected design was a cylindrical charge with a buffer material between the shaped solid projectile and the charge. The projectile nose shape and weight were similar to the 75-mm projectile presently used. The depressions formed by this design are caused by a combination of explosive pressure and projectile impact. The shock wave passing through the projectile into the weld test plate being tested apparently aids in causing cracks, as some plates showed weld cracks with little or no depression being formed. The individual significance of each of these effects was not evaluated--just the overall depression shape and depth and crack length.

One of the effects noted in the selected design was that charge sizes consisting of more than 4,767 grams (g) of 40% dynamite caused smaller depressions in the test plates than those containing less than 4,767 g. Possibly, this effect was caused by the disintegration of the projectile before the depression was formed in the plate. The inconsistent results noted in the testing may be the result of this effect. Considerable weld cracking occurred with relatively minor plate deformation, indicating that either the welds were below standard or other mechanisms contributed to the cracking.

Further improvements in this shaped charge design are not believed warranted. An improved design will probably not yield consistent impressions of proper shape, depth, and weld crack length in 1.5-in. welded armor plate to meet MIL-STD-1941(MR) weld integrity requirements.

4.0. RECOMMENDATIONS

- Discontinue development of present shaped charge designs using medium-velocity explosives with buffers and projectiles to simulate the impression, shape, and depth of a ballistic projectile impacting upon 1.5-in. weld test plates.

- Investigate direct contact charges of low-velocity explosives with momentum plates. Development of a new set of acceptance/rejection criteria would be required, because weld cracking will occur with less material strain (projectile impression). Weld-cracking characteristics and length rather than the shape and depth of impression would govern the acceptance criteria.

- Investigate a gas-driven projectile accelerator, which can be used in a protective frame to duplicate the ballistic projectile impact impression.

5.0. DISCUSSION

5.1. Background

Standard physical test methods to evaluate materials do not provide all the information needed for armor plate weld confidence. Weld specimens behave somewhat differently under high-velocity impact (explosive or projectile impact) than under the influence of forces applied less abruptly. Materials generally act more brittle at high strain rates. Confidence in military vehicle armor plate welds is currently established through a Ballistic Test Procedure to test for minimum weld properties.

The program that is the subject of this report was instituted to develop a less costly procedure ("shaped charge"), which need not be performed at a ballistic test range. A major constraint was that the shaped charge method must develop an impression with a depth, contour, and weld-cracking effect similar to the ballistic projectile impact on a comparable weld test plate. Such a demonstration would allow use of the ballistic test specification acceptance criteria when evaluating test welds subjected to shaped charge testing.

Generally, the shaped charges used by the military in munitions, by the oil-well industry to perforate casings and cut pipe, and for other civilian applications have been designed for penetration or cutting. The charge is designed to increase jet velocity above the explosive detonation velocity (burning rate), causing spalling and ejection of molten material from the target face, with little deformation to the area surrounding the target.

For this test program, considerable deformation of tough, high-tensile, armor plate was required. The plate size and type chosen by TACOM for this program was 1.5 in. thick per MIL-A-12560G(MR).[2] To generate a depression similar to the ballistic projectile impression, the charge had to apply the force to the limited area of the 75-mm projectile impact cross section without having the charge jet cause spalling of the plate. Because of the high energy requirement and the limited area to act on, a high-energy output explosive was required. Such explosives generally have high densities (mass) and high detonation velocities. They generate a high-pressure detonation wave, which causes spalling on the back of the test targets.

Spalling on the back surface is caused when the incident compressive wave reaches a free surface and is reflected as a tension wave. The incident compressive wave and reflected tensile wave are cumulative. At some instant, the tensile stress will be well above the critical normal fracture stress of the plate material. The material then fails in tension, and a layer of material is ejected from the plate. This is called "back-side" spalling. Face spalling is caused by hydrodynamic flow induced when a hypervelocity jet penetrates the target and hydrodynamically expels the material. Because of the extreme pressure, much of this material is molten.

Impulsive loads (those that are applied by ballistic projectiles or by shaped charges) on materials cause a reaction that is very different from static loads. Under static loads, the stresses and strains are distributed throughout the body so that every part of the body participates in the reaction to loading. Time allows stresses and strains to distribute uniformly throughout the target. Under impulsive (i. e., ballistic or explosive) loading, the stresses are transient and highly local, producing localized strains. An explosive shock, in general, leaves a metal piece in a nonhomogeneous state. Because the stress wave decays as it moves through the body, parts are subjected to various magnitudes and durations of pressures. Deformation and fractures may occur in one part independently of what happens in another. Time becomes paramount under impulsive loading, controlling to a large extent the particular effects produced.

The ballistic projectile impact studied for this program showed that the point where the projectile impacted was subjected to impulsive loading. The localized stresses and strains in the material generated a small depression at the center of the impact. As the projectile and plate deformed, loading time increased sufficiently to allow additional deformation of the surrounding test plate, generating the conical depression.

In one approach, charges were tested without projectiles in an attempt to concentrate some of the charge energy from the detonation wave into a jet to produce a deformation similar to the impression made by the projectile. The charge pressure wave pulse was to form the conical depressions without causing face or back-side spalling. A second approach used a projectile to concentrate and direct the energy from the charge, driving the projectile into the test plate. Both approaches were tested with and without charge-shaping cavities.

5.2. Test Program

The program implemented to develop the charge system and test procedure consisted of seven tasks:

- Task 1--Conduct literature search and armor weld test specifications review
- Task 2--Define explosive test procedures and test various shapes until the desired effects are achieved
- Task 3--Select the most promising design for testing and fabricate charges
- Task 4--Perform tests using reduced-size specimens
- Task 5--Evaluate eight sizing tests from Task 4 and estimate charge size for the four comparison tests in Task 6
- Task 6--Based on reduced-size specimens, perform four comparison tests on full-size weld test plates for comparison with ballistic tests
- Task 7--Prepare and submit final report.

5.3. Armor Weld Test Specification Review and Literature Search (Task 1)

The TACOM Contracting Officer Technical Representative (COTR) selected the plate thickness and armor material for final charge design evaluation. The TACOM COTR selected 1.5-in.-thick wrought homogeneous armor plate per MIL-A-12560G(MR). Welding of test plates and weld test procedures were to be as defined in MIL-STD-1941(MR).

MIL-STD-1941(MR),[1] which contains the requirements for ballistic testing of welded armor and MIL-A-12560G(MR),[2] the specification for steel, wrought, homogeneous armor plate, were reviewed to determine the basic plate material specifications applicable to 1.5-in. wrought steel armor plate. MIL-W-46086(MR) was originally identified in the contract as the specification to be used to test welded armor. This specification was superseded by MIL-STD-1941(MR), and the new specification was used to specify the welded armor requirements for this program. NRL(MR)1255[3] and NRL3790[4] were also reviewed.

Two standard weld test plates, prepared according to MIL-STD-1941(MR), were supplied by TACOM. Both plates were approximately 36- by 36- by 1.5-in. thick, containing three weld areas. Two welds ran parallel completely across the plate, approximately 12 in. apart and 12 in. from each edge. The third weld, at the center of the plate, was perpendicular to the first two, connecting them and forming an H. All three were double-V through welds, welded from both sides, similar to the weld joint in MIL-STD-1941(MR) (Appendix A, Procedure 1, Joint A-A).[1]

Plate 1 had no test impressions and was marked SCRAP. Plate 2 had two impressions. TACOM indicated that both impressions were acceptable. Both showed a conical depression with a cylindrical impression in the center formed by the projectile.

The measurement of the larger depression, taken from the bottom of a 14.5-in. straight edge laid across the depression to the bottom of the depression, was 1.7 in. The cylindrical imprint of the projectile at the bottom of the larger conical depression was 2.5 in. in diameter (D) by 0.375 in. deep. The smaller conical depression, measured in a similar way, was 0.875 in. deep, with a 2.25-in.-D by 0.312-in.-deep cylindrical imprint. These measurements were the basis for comparing test results.

The following parameters were used as a basis for comparing charge design and evaluating results:

- Impact energy equivalent to a 75-mm PPM1002 projectile approximately 6,810 g impacting at 1,200 ±25 ft/s.

- Minimum and maximum depression limits for ballistic projectile impact deformation of the 1.5-in. armor plate:

  - Conical depression measured from the bottom of a 14.5-in. straight edge: minimum = 0.875 in., maximum = 1.69 in.

  - Imprint of projectile at bottom of conical depression: approximate maximum = 2.5 in. in D by 0.375-in. deep; approximate minimum = 2.25 in. in D by 0.312-in. deep.

  - Armor plate: 1.5-in. wrought homogeneous armor [MIL-A-12560G(MR),[2] Class 1]; quench and tempered; surface hardness = HB-311; yield strength = 123,000 pounds per square inch (psi); tensile strength = 135,000 psi.

A literature search was conducted for reports, papers, patents, and textbooks discussing high-rate metal forming and shaped charge technology. Most of the information found dealt with shaped charge parameters for penetration charges or charges used to initiate other explosive charges in munitions. These categories of charge design were not applicable because they generate hypervelocity jets designed to melt, fragment, and expel material from the target surface. Little or no target deformation occurs adjacent to the jet impact area.

Two patents described methods of accelerating projectiles and protecting the projectile from the detonation shock wave. One describes a charge using a parabolic or conical cavity filled with wax to accelerate a solid steel projectile.[5] Another describes a cylindrical charge, with alternating layers of a metal powder, which acts as an attentuator, and metal disks.[6] This assembly formed a projectile after detonation.

Two pieces of literature described a direct explosive test using low-velocity explosives to test 0.75- and 1-in. ship plate and armor plate.[7,8] The explosive was developed by the Trojan Powder Company, which is no longer in business. The report states that the direct explosion test is more applicable to Navy ship plate, because tank armor--a harder, tougher material with higher tensile strength--does not respond as predictably to this type testing. Thicker plate was not tested.

5.4. Charge Design and Development (Task 2)

Charge designs were evaluated for their ability to form the required impression in the 1.5-in. armor plate selected by TACOM for this program. Shaped charges generally concentrate or focus the blast against a surface, causing front-face spalling as a result of jet action or back-side spalling from the high-velocity shock wave. Standoff charges, charges detonated away from the test plate with no focusing, are used for bulge testing and general metal forming. They form a spherical depression in a free-formed plate, which does not subject the plate to the local strains or shock waves developed by the impact from a ballistic projectile.

To simulate the projectile impact, the charge must generate an extremely high force in a localized area equivalent to the projectile imprint. In addition, the duration that this force is acting on the plate must be long enough to allow the large mass of the plate to move (strain), thereby forming a conical depression. High forces at high velocity would penetrate the plate with little strain in adjacent areas.

Fifty-three tests were conducted to study the effects of various explosives, energy-focusing methods, projectile systems, buffers, and standoff distances. Test results were used to determine a charge design that would cause the required impression with associated cracking in the TACOM test plates. Most of the Task 2 testing was conducted on available scrap (low-carbon steel plate), thereby reducing program material cost and allowing additional testing.

Testing was performed as materials and explosives became available. Some testing was rearranged to suit the weather. Literature searches and reviews suggested changes and designs which were incorporated into the program. For these reasons, some tests were conducted out of logical sequence; others were canceled (Charges 1, 5, 6, 13-15, 17-19, 23, 30, 55, and 56).

Four explosives were used in this program:

- Nitroguanidine--a relatively slow-detonating, low-density explosive [3,400 meters per second (m/s) and 0.6 density].

- Detasheet C--a relatively high-velocity explosive (6,800 m/s, 1.48 density)

- 40% Super Gel Dynamite--an easily procured, higher density, low-cost explosive (4,600 m/s and 1.5 density)

- T200W--a relatively slow detonating explosive (3,600 m/s and 1.05 density).

Nitroguanidine was used because it is safe and easy to load, its density is easily varied, it has a low detonating velocity, and it does not generate dangerous byproducts. Detasheet C was used because it is easily handled; has relatively high density; can be easily pressed and formed; and has a predictable, high, energy output. It is also a very stable and consistent explosive. The dynamite selected (40% Super Gel) is easily procured in small quantities; is inexpensive; can be formed easily; has a high density; and has a relatively low velocity, which would reduce spall damage. Its cost and availability permit inexpensive charge fabrication and avoid the need for storing large quantities of explosives. (Table 5-1 lists explosives characteristics.) T200W was tried as a replacement for the dynamite because it is easy to handle and load. Because it is used for seismic testing, the shock and power are accurately controlled.

Initial testing was conducted to observe the characteristics of simple, shaped charges with and without jet shaping cavities. The effect of standoff distances, along with explosives of high and low detonating velocities, was evaluated. This testing was done to determine whether simple, shaped charges could be used to form depressions in plates without the deleterious effects of spalling.

The development testing conducted during Task 2 is presented in four parts:

- Shaped charges with cylindrical cavities

- Solid cylindrical charges

- Solid cylindrical charges with projectiles

- Shaped charges with formed cavities and projectiles.

Table 5-1. Explosives Used

■ Explosive:	Detasheet C
Manufacturer:	E. I. duPont de Nemours & Company Wilmington, Delaware
Detonation Velocity:	23,000 ft/s at 1.48 g/cc density
■ Explosive:	40% Super Gel Dynamite
Manufacturer:	Independent Explosives Scranton, Pennsylvania
Detonation Velocity:	15,000 ft/s at 1.5 g/cc density
■ Explosive:	Nitroguanidine
Manufacturer:	J. S. Bower and Associates Pomona, California
Detonation Velocity:	11,200 ft/s at 0.6 g/cc density 13,800 ft/s at 0.8 g/cc density
■ Explosive:	T200W
Manufacturer:	Thermex Energy Corporation Dallas, Texas
Detonation Velocity:	12,000 ft/s at 1.05 g/cc density

5.4.1. Shaped Charges With Cylindrical Cavities. These charges generally consisted of cylindrical plastic or metal tubes into which the explosive was loaded. In charges with cavities, the end of the charge facing the test target plate contained a cylindrical cavity. The axis of charge and cavity coincided.

Three charges contained a low-velocity explosive (Nitroguanidine) and three contained a relatively high-output explosive (Detasheet C). Two cavities contained polyethylene liners, one had a copper flyer plate, and two had flyer plates fabricated from powdered iron. All flyer plates were placed in the cavity top (next to the explosive).

Detonation of these six charges on 1.5-in., low-carbon-steel plate produced a crater on the face of the target caused when the material was ejected by the charge jet. The flyer plates tended to increase this effect. Detailed parameters for these charges are given in Table 5-2 (Charges 2-4 and 10-12). Figure 5-1 shows a typical charge setup and typical plate damage. This approach produced a cavity in the test plate with no plate deformation adjacent to the jet impingement area.

5.4.2. Solid Cylindrical Charges. This group consisted of 19 simple cylinders filled with explosive. Variations were made in:

- Charge size
- Explosive
- Standoff distance with different buffer materials in the interface
- Charge initiation by a single point or by "plane wave generator" (PWG)
- Detonating charges in air, under water, or under sand
- Plywood, steel plate, or Cerro Alloy as a momentum plate (sacrificial plate) to eliminate back-side spalling.

A PWG detonates uniformly across the top face of the charge by using two explosives of different velocities in a cone shape. The faster detonating explosive, in this case Detasheet C (23,000 ft/s) was used with either Nitroguanidine (11,200 ft/s) or 40% dynamite (15,000 ft/s). The Detasheet is formed into a cone and is the hypotenuse of the right-angle triangle; the slower explosive fills the cone and acts as the triangle leg at the axis of the cylindrical charge.* As the high-velocity explosive detonates, it detonates the low-velocity explosive, at the same

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*Apex angle of cone = 2[arc cos(slower explosive, ft/s)]/
(Detasheet, ft/s)

Table 5.2. Charge Development[1] [2] [3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive	Deto-nator	Charge Cover-ing	Test Plate	Results		Remarks
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Mate-rial	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Dis-tance (in.)	Buffer	Name/ Weight (g)			Material/ Thickness (in.)	Front/ Back	Impres-sion. Diam./ Depth (in.)	
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
1	---	---	---	---	---	---	---	---	---	---	---	---			No test.
2	3.1/ 3.5	Cyl./ 1.5/ 2.0	---	CU/ Disk/ ---	1.5/ 0.062	---	0	---	NG/225	P	---	LCS/ 1.5	Spall/ ---	1/ 0.41	Figure 5-1.
3	3.1/ 3.5	Cyl./ 1.5/ 1.25	---	---	---	---	0	---	NG/239	P	---	LCS/ 1.5	Spall/ ---	1.25/ 0.26	Figure 5-1.
4	3.1/ 3.5	Cyl./ 1.63/ 1.25	---	---	---	---	0	---	NG/149	P	---	LCS/ 1.5	Spall/ ---	1.25/ 0.26	Figure 5-1.
5	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
6	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
7	1.5/ 1.5	---	---	---	---	---	0	---	D/70.5	P	---	LCS/ 1.5	---/ Spall	1.5/ 0.14	Figure 5-1.
8	1.5/ 1.5	---	---	---	---	---	0	---	D/70.5	P	(4)	LCS/ 1.5	---/ Spall	1.5/ 0.51	Figure 5-2.
9	1.5/ 1.5	---	---	---	---	---	0	---	NG/32	P	---	LCS/ 1.5	---/ ---	0/ 0.02	Figure 5-1.
10	1.0/ 1.25	Cyl./ 0.5/ 0.5	---	---	---	---	0	---	D/22	P	---	LCS/ 1.5	Spall/ ---	0.5/ 0.23	Figure 5-1.
11	1.0/ 1.25	Cyl./ 0.5/ 0.5	---	Iron/ Disk/ Iron Powder	0.5/ 0.13	---	0	---	D/23	P	---	LCS/ 1.5	Spall/ ---	0.5/ 0.30	Figure 5-1.

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel *Cu = Copper Al = Aluminum* Fe = Iron.
2 Explosives: NG = Nitroguanidine D = Detasheet C 40% = Dynamite, 40% Super Gel.
3 Detonator: P = Point PWG = Plane Wave Generator.
4 Charge placed into 1.5-in. bore of 8- by 8- by 14-in. steel block.

Table 5.2. Charge Development (continued)[1 2 3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive			Test Plate	Results		
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Material	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Distance (in.)	Buffer	Name/ Weight (g)	Detonator	Charge Covering	Material/ Thickness (in.)	Front/ Back	Impression, Diam./ Depth (in.)	Remarks
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
12	1.0/ 1.25	Cyl./ 0.88/ 0.5	---	Iron/ Disk/ Iron Powder	0.88/ 0.13	---	0	---	D/21	P	---	LCS/ 1.5	Spall/ ---	0.5/ 0.29	Figure 5-1.
13	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
14	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
15	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
16	3.15/ 3.85	Cyl./ 1.75/ 1.0	---	SS/Disk Ring/ ---	(4)/ 0.40	154	0.6	Air	NG/254	P	---	LCS/ 1.5	---/ ---	1.13/ 0.13	Figure 5-7.
17	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
18	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
19	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
20	1.44/ 1.88	---	---	---	---	---	0	---	NG/35	P	Water	LCS/ 0.75	---/ ---	---/ 0.13	
21	1.44/ 1.88	---	---	---	---	---	0.5	Air	NG/35	P	Water	LCS/ 0.75	---/ ---	---/ 0.03	
22	1.44/ 1.88	---	---	---	---	---	0.5	Water	NG/35	P	Water	LCS/ 0.75	---/ ---	---/ 0.09	
23	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
24	1.44/ 1.88	---	---	---	---	---	0.5	Air	NG/D / 28/108	P	Water	LCS/ 0.75	---/ ---	---/ 0.31	
25	1.44/ 1.88	---	---	---	---	---	0.5	Water	D/63	P	Water	LCS/ 0.75	---/ ---	---/ 1.81	Inverted bell shape.

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel Cu = Copper Al = Aluminum Fe = Iron.
2 Explosives: NG = Nitroguanidine D = Detasheet C 40% = Dynamite, 40% Super Gel.
3 Detonator: P = Point PWG = Plane Wave Generator.
4 Projectile was 1.5 in. D disk 0.4 in. thick with 2.02 in. OD ring pressed on.

Table 5.2. Charge Development (continued)[1] [2] [3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive			Test Plate	Results		Remarks
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Material	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Distance (in.)	Buffer	Name/ Weight (g)	Detonator	Charge Covering	Material/ Thickness (in.)	Front/ Back	Impression, Diam./ Depth (in.)	
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
26	1.44/ 1.88	---	---	---	---	---	0.25	Polyethylene	D/63	P	Water	LCS/ 0.75	---/ Spall	---/ 1.13	
27	1.13/ 2.5	Cyl./ 0.88/ 1.0	---	LCS/ Disk/ ---	0.88/ 0.25	19	1.0	Air	D/65	PWG	---	LCS/ 0.75	---/ ---	---	Projectile at bottom of charge cavity. Figure 5-1.
28	1.13/ 2.5	Cyl./ 0.88/ 1.0	---	LCS/ Disk/ ---	0.88/ 0.25	19	0	---	D/63	PWG	---	LCS/ 0.75	Spall/ ---	0.02/ 0.2	Projectile at top of charge cavity. Figure 5-1.
29	1.13/ 2.5	Cyl./ 0.88/ 1.0	---	LCS/ Disk/ ---	0.88/ 0.50	38	0	---	D/63	PWG	---	LCS/ 0.75	Spall/ ---	0.14/ 0.15	Projectile at top of charge cavity. Figure 5-1.
30	---	---	---	---	---	---	---	---	---	---	---	---	---	---	No test.
31	2.0/ 5.0	Para./ ---/ ---	Wax	LCS/ Cyl./ ---	1.0/ 1.5	130	2.0	Air	D/229	P	---	LCS/ 0.75	Spall/ ---	---/ 0.1	Figure 5-8.
32	2.0/ 5.0	Para./ ---/ ---	Wax	LCS/ Cyl./ ---	1.0/ 1.5	134	3.25	Air	D/241	P	---	LCS/ 0.75	Spall/ ---	---/ 0.1	Figure 5-8.
33	2.0/ 5.0	Con./ ---/ ---	Wax	LCS/ Cyl./ ---	1.0/ 1.5	131	12.25	Air	D/293	P	---	LCS/ 0.75	---/ ---	1.0/ 0.03	Wave shaping disk in explosive charge. Figure 5-8.
34	2.1/ 7.0	---	---	SS/ Layered Disks/ Al	2.0/ 0.94	189	2.0	Air	NG 0.72/ 229	P	---	LCS/ 0.75	---/ ---	---/ 0.25	Similar shape to ballistic plate. Figure 5-6.
35	2.1/ 7.0	---	---	SS/ Layered Disks/ Al	2.0/ 1.0	264	2.0	Air	40%/553	P	---	LCS/ 0.75	---/ ---	2.5/ 0.346	Fractured projectile. *Figure 5-6.*

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel Cu = Copper Al = Aluminum Fe = Iron.
2 Explosives: NG = *Nitroguanidine D* = *Detasheet C 40%* = *Dynamite. 40% Super Gel.*
3 Detonator: P = Point PWG = Plane Wave Generator.

Table 5.2. Charge Development (continued)[1] [2] [3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive	Deto-nator	Charge Cover-ing	Test Plate	Results		Remarks
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Mate-rial	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Dis-tance (in.)	Buffer	Name/ Weight (g)			Material/ Thickness (in.)	Front/ Back	Impres-sion. Diam./ Depth (in.)	
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
36	2.1/ 7.0	---	---	SS/ Layered Disks/ Al	2.0/ 1.7	474	2.0	Air	40%/488	P	---	LCS/ 0.75	---/ ---	2.1/ 0.377	Figure 5-6.
37	2.1/ 7.0	---	---	SS/ Layered Disks/ Al	2.0/ 1.7	445	2.0	Air	D/382	P	---	LCS/ 0.75	---/ ---	2.2/ 0.482	Figure 5-6.
38	2.1/ 7.7	---	---	SS/ Layered Disks/ Iron	2.0/ 1.7	416	2.0	Air	40%/582	P	---	LCS/ 0.75	---/ ---	2.1/ 0.420	Figure 5-6.
39	3.5/ 7.0	Cyl./ 2.1/ 3.7	---	SS/ Layered Disks/ Iron	2.0/ 1.7	403	0	---	40%/1490	PWG	---	LCS/ 0.75	Spall/ Spall	2+/	Through hole (disk stack at top of cavity). Figure 5-9.
40	2.1/ 7.8	---	---	SS/ Layered Disks/ Iron	2.0/ 1.7	395	0	---	40%/568	P	---	LCS/ 0.75	---/ ---	2.1/ 0.441	Figure 5-6.
41	4.0/ 5.8	Cyl./ 2.1/ 3.3	---	SS/ Layered Disks/ Iron	2.0/ 1.7	417	0	---	40%/1604	PWG	---	LCS/ 0.75	Spall/ ---	---/ ---	Projectile ex-tends 0.5 in. from cavity bottom (plate fractured). Figure 5.9.
42	4.0/ 5.8	Cyl./ 2.1/ 3.3	---	SS/ Layered Disks/ Iron	2.0/ 1.7	416	0	---	40%/1670	PWG	---	LCS/ 1.5	---/ Spall	---/ ---	Fractured back face. Figure 5-9.

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel Cu = Copper Al = Aluminum Fe = Iron.
2 Explosives: NG = Nitroguanidine D = Detasheet C 40% = Dynamite, 40% Super Gel.
3 Detonator: P = Point PWG = Plane Wave Generator.

Table 5.2. Charge Development (continued)[1 2 3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive	Deto-nator	Charge Cover-ing	Test Plate	Results		Remarks
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Mate-rial	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Dis-tance (in.)	Buffer	Name/ Weight (g)			Material/ Thickness (in.)	Front/ Back	Impres-sion. Diam./ Depth (in.)	
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
43	4.0/ 5.8	Cyl./ 2.1/ 3.3	Wax	SS/ Layered Disks/ Iron	2.0/ 2.3	786	3.5	Air	40%/2110	PWG	---	LCS/ 1	---/ ---	---/ 0.28	Fractured projectile. Figure 5-9.
44	4.0/ 3.3	Cyl./ 3.1/ 1.3	Wax	SS/ Solid Disk/ ---	2.3/ 0.5	222	0	---	40%/1082	PWG	---	LCS/ 1	---/ Spall	---/ 1.13	Back-Spall. Figure 5-10.
45	4.0/ 3.3	Cyl./ 3.1/ 1.3	Wax	SS/ Solid Disk/ ---	2.3/ 0.5	242	1	Air	40%/1085	PWG	---	LCS/ 1	---/ ---	2.13/ 1.06	Gas erosion at edges of disk impression. Figure 5-10.
46	4.0/ 3.3	Cyl./ 3.1/ 1.3	Wax	SS/ Solid Disk/ ---	2.3/ 0.5	243	2	Air	40%/1088	PWG	---	LCS/ 1	---/ ---	2.0/ 1.19	Gas erosion at edges of disk impression. Figure 5-10.
47	4.0/ 3.3	Cyl./ 3.1/ 1.3	Wax	SS/ Solid Disk/ ---	2.3/ 0.5	243	0.5	Air	40%/1089	PWG	---	LCS/ 1	---/ ---	---/ ---	Plate fracture-gas erosion at edge of disk impression. Figure 5-10.
48	5.3/ 4.4	Cyl./ 4.0/ 1.5	Wax	LCS/ Stepped Disk/ ---	3.5/ 0.88	793	1.0	Air	40%/2294	PWG	---	LCS/ 1	---/ ---	2.5/ 2.4	Gas erosion at edges of disk impression. Figure 5-10.
49	5.3/ 5.0	Cyl./ 4.0/ 1.5	Wax	LCS/ Stepped Disk/ ---	3.5/ 1.4	1022	1.0	Air	40%/2293	PWG	---	LCS/ 1	---/ ---	2.0/ 1.88	Gas erosion at edges of disk impression. Figure 5-10.

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel Cu = Copper Al = Aluminum Fe = Iron.
2 Explosives: NG = Nitroguanidine D = Detasheet C 40% = Dynamite, 40% Super Gel.
3 Detonator: P = Point PWG = Plane Wave Generator.

Table 5.2. Charge Development (continued)[1 2 3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive			Test Plate	Results		Remarks
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Material	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Distance (in.)	Buffer	Name/ Weight (g)	Detonator	Charge Covering	Material/ Thickness (in.)	Front/ Back	Impression. Diam./ Depth (in.)	
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
50	5.3/ 5.5	Cyl./ 3.8/ 1.3	Wax	SS/ Shaped/ ---	5.3/ 1.7	2026	1.0	Air	40%/2386	PWG	---	LCS/ 1	---/ ---	2.5/ 1.63	Excellent. Figure 5-10.
51	5.3/ 5.5	Cyl./ 3.8/ 1.3	Wax	SS/ Shaped/ ---	5.3/ 1.7	2206	1.0	Air	40%/2376	PWG	---	A/ 1.5	---/ ---	2.8/ 0.19	Figure 5-10.
52	5.3/ 5.5	Cyl./ 3.8/ 1.3	Wax	SS/ Shaped/ ---	5.3/ 1.7	2216	2.0	Air	40%/3133	PWG	---	A/ 1.5	---/ ---	2.8/ 0.16	Figure 5-10.
53	5.3/ 4.0	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0.25	Polyethyene	40%/3003	PWG	---	A/ 1.5	---/ Spall	5.3/ 1.4	
54	7.13/ 3.63	Cyl./ 5.3/ 1.5	Wax	A/ Shaped/ ---	7.13/ 3.0	7893	1	Air	40%/3941	PWG	---	A/ 1.5	---/ ---	2.0/ 2.38	Pipe 8.625 O.D. by 7.125 I.D. by 5.125 long. Figure 5-11. (4)
55	---	---	---	---	---	---	---	---	---	---	---	---	---	---	Proof test of drum.
56	---	---	---	---	---	---	---	---	---	---	---	---	---	---	Proof test of drum.
57	2.5/ 3.5	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0.5	Water	40%/440	(5)	Water	LCS/ 0.75	---/ ---	2.38/ 1.27	Spherical depression.
58	2.5/ 3.0	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0.5	Water	40%/435	PWG	Water	LCS/ 0.75	---/ ---	---/ ---	Fracture plate.

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel Cu = Copper Al = Aluminum Fe = Iron.
2 Explosives: NG = Nitroguanidine D = Detasheet C 40% = Dynamite, 40% Super Gel.
3 Detonator: P = Point PWG = Plane Wave Generator.
4 Charge contained and concentrated by heavy wall pipe - much shapnel.
5 Charge detonated at vertical center.

Table 5.2. Charge Development (continued)[1 2 3]

Charge No.	Charge	Cavity		Projectile			Standoff		Explosive	Deto- nator	Charge Cover- ing	Test Plate	Results		Remarks
	Diam./ Length (in.)	Shape/ Diam./ Length (in.)	Buffer Mate- rial	Material/ Type/ Powder	Diam./ Length (in.)	Weight (g)	Dis- tance (in.)	Buffer	Name/ Weight (g)			Material/ Thickness (in.)	Front/ Back	Impres- sion. Diam./ Depth (in.)	
	A/B	---/ C/D	E	F	G/H	I	S	J	K/L	---	---	M/N	---	O/P	
59	2.5/ 3.5	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0.5	Air	40%/440	(4)	Water	LCS/ 0.75	---/ ---	2.8/ 0.44	
60	2.5/ 3.5	(5)/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0	---	40%/440	PWG	Water	LCS/ 0.75	---/ Spall	3.0/ 0.75	Figure 5-3.
61	2.5/ 4.13	(6) / ---/ ---	---	---/ ---/ ---	---/ ---	---	0	(7)	40%/440	PWG	Sand	LCS/ 0.75	---/ Spall	---/ 3	Figure 5-4.
62	2.5/ 3.25	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0	---	40%/440	PWG	Sand	LCS/ 0.75	---/ Spall	---/ 3.25	
63	2.5/ 3.25	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0	(8)	40%/440	PWG	Sand	LCS/ 0.75	---/ ---	2.75/ 1.88	Figure 5-4.
64	2.5/ 6.25	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0	---	NG/422	PWG	Sand	LCS/ 0.75	---/ Spall	2.75/ 2.63	
65	2.5/ 5.25	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0	(9)	D/600	PWG	Sand	A/ 1.5	---/ ---	2.63/ 0.5	Figure 5-4.
66	2.5/ 6.75	---/ ---/ ---	---	---/ ---/ ---	---/ ---	---	0	(9)	D/660	PWG	Sand	A(10)/ 1.5	---/ ---	2.25/ 0.3	Charge placed over weld. Figure 5-4.

1 Materials: LCS = Low Carbon Steel A = Steel Armor Plate SS = Stainless Steel Cu = Copper Al = Aluminum Fe = Iron.
2 Explosives: NG = Nitroguanidine D = Detasheet C 40% = Dynamite. 40% Super Gel.
3 Detonator: P = Point PWG = Plane Wave Generator.
4 Charge detonated at vertical center.
5 Sphrical convex end in contact with test plate.
6 Charge bottom is inverted-truncated cone in contact with test plate.
7 8 by 8 by 0.75-in. plywood used as sacrificial plate (momentum plate) with test plate.
8 0.75-in. by 6.25-in. by 6.25-in. LCS plate used as sacrificial plate (momentum plate) under test plate.
9 6.0 in. D by 0.31-in. thick plate of Cerro Alloy used as sacrificial plate (momentum plate) under test plate.
10 36 by 36 by 1.5 armor plate marked "scrap" charge placed on weld.

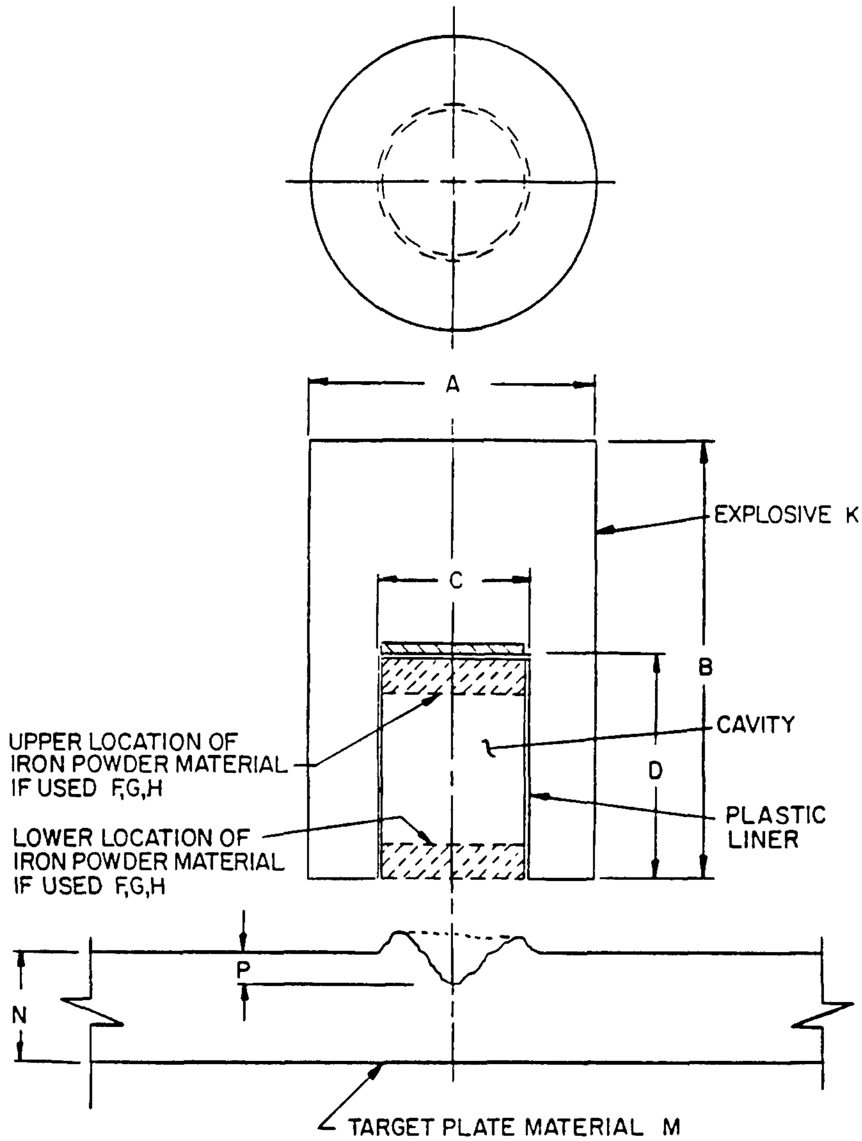


Figure 5-1. Typical Cylindrical Charge Setup With Cylindrical Cavity--Charges 2, 3, and 4 (Letters in illustrations are keyed to columns in Table 5-2.)

rate along the hypotenuse that the low-velocity explosive is detonating along the leg of the triangle axially toward the base of the cone axis. This action causes all the explosive to detonate at the cone base/cylindrical charge interface at the same instant, thereby generating a plane wave detonation which continues through the charge.

A momentum plate (sacrificial plate) prevents back-side spalling by absorbing the compressive shock wave after it passes through the test plate. Upon reflecting from a free surface of the momentum plate, the compressive wave reflects as a tensile wave. The tensile wave cannot reenter the test plate because the two separate. The shock wave energy is then dissipated by fracturing the momentum plate, leaving the test plate intact.

This group of 19 solid cylindrical charges is discussed in six sets of similar configurations (A through F). Details of charge dimensions, explosive loading, standoff distances, and measurements of results are given in Table 5-2. The table also lists the figure in the report that relates to the specific charge.

Set A (Charges 7-9) consisted of three simple cylindrical charges with Charges 7 and 8 containing Detasheet C and Charge 9, Nitroguanidine. Charges 7 and 9 were contact cylindrical charges without containment; Charge 8 was a contact charge placed into the 1.5-in. bore of an 8- by 8- by 14-in. carbon steel block to contain and concentrate the energy of the charge (Figure 5-2). Following detonation on a 1.5-in., low-carbon-steel plate, Charges 7 and 8 produced back-side spalling; Charge 9 did not. Measurements indicated that Charge 8 produced approximately $3\frac{1}{2}$ times the depression depth of Charge 7 (0.51 vs. 0.14 in.). No significant depression was formed by Charge 9. The depression caused by Charge 8 was local, confined to the charge diameter, and did not appear to cause any deformation of the plate adjacent to the depression.

Set B (Charges 20-22) observed the effect of a standoff with air and water as a buffer. All three used Nitroguanidine explosive detonated on 0.75-in., low-carbon-steel plate, under approximately 10 in. of water. The water contained and concentrated charge energy and modulated ambient noise. Standoff distances were 0 in. for Charge 20 and 0.5 in. for Charges 21 and 22. The resultant depressions were 0.13, 0.09, and 0.09 in. respectively. No spalling of the face or back of the plate was noted.

Set C (Charges 62 and 64) compared 40% dynamite (Charge 62) and Nitroguanidine (Charge 64) along with the PWG detonation method. Both were contact charges detonated on 0.75-in. low-carbon-steel plate under sand to contain and concentrate charge energy. Back-side spalling resulted from both charges. Depression depths were 3.25 in. for Charge 62 and 2.63 in. for Charge 64. These measurements indicated that some form of buffer was required to control back-side spalling of the target plate. The depressions did not have the characteristic projectile impact shape.

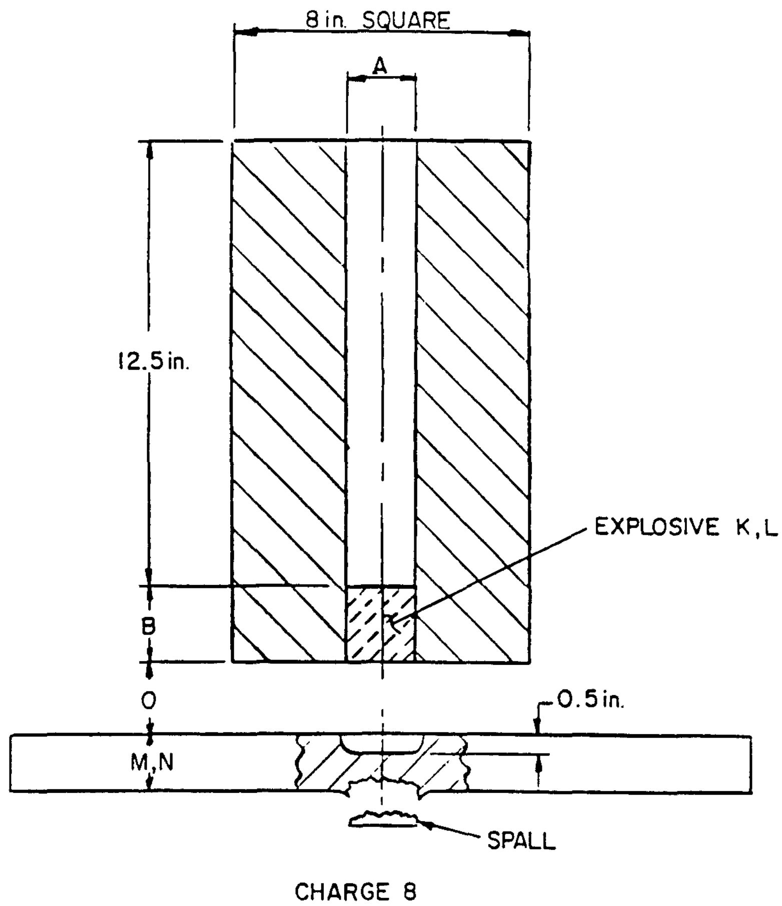


Figure 5-2. Solid Cylindrical Charge With Steel Block Containment--Charge 8 (Letters in illustrations are keyed to columns in Table 5-2.)

Set D (Charges 25, 26, and 53) compared Charge 25 (a 0.5-in. standoff and water in the interface) with Charges 26 and 53 (0.25-in. standoff and polyethylene in the interface). Charges 25 and 26 contained Detasheet C; Charge 53 contained 40% dynamite. Charges 25 and 26 were detonated under 10 in. of water on a 0.75-in., low-carbon-steel test plate, and Charge 53 was in air on 1.5-in. armor plate. Both charges with polyethylene in the interface caused back-side spalling. Charge 26 caused a 1.13-in. spherical depression, and Charge 53 caused a 1.4-in. spherical depression approximately the diameter of the charge. Charge 25 generated an inverted bell-shaped depression approximately 1.8 in. deep. This depression was not the typical conical depression required; it had no projectile-like imprint at the center.

Set E (Charges 57-60) compared the effect of detonating an explosive at the longitudinal center of the charge with detonating a charge on top using a PWG. The four charges (57-60) were loaded with 40% dynamite and detonated under 10 in. of water. Charges were detonated on 0.75-in., low-carbon-steel plate supported with 3.5-in.-D bar stock on 12-in. centers. Charge 57 was center-detonated with a 0.5-in., water-filled standoff; Charge 59 was center-detonated with a 0.5-in., air-filled standoff. Charge 58 was top-detonated using a PWG with a 0.5-in., water-filled standoff, and Charge 60 was top-detonated using a PWG in contact with the test plate. The end of Charge 60 contacting the test plate was shaped as a convex sphere (Figure 5-3). Results indicated that center-detonated charges direct less energy toward the test plate and act similar to smaller top-detonated charges. These charges also tend to generate spherical depressions without the characteristic cone-shaped projectile impact impression. Charge 60 (with the spherical end) generated a spherical depression that was slightly conical toward the outside edge. It also caused back-side spalling.

Set F (Charges 61, 63, 65, and 66) observed the effect of momentum plates (sacrificial plates). Charges 61 and 63 contained 40% dynamite; Charges 65 and 66 contained Detasheet C. Detasheet C, with a higher detonation velocity and energy, was used to develop a more severe potential for back-side spalling. The momentum plates were made of three materials: plywood for Charge 61, a 0.75-in. steel plate for Charge 63, and a cast Cerro Alloy for Charges 65 and 66. To allow the use of more explosives and still maintain the 2.25-in.-D (approximately) projectile impact impression, Charge 61 was modified with an inverted truncated cone on the end in contact with the test plate. The remaining three charges were simple solid cylinders. All were detonated under approximately 14 in. of sand using PWGs; all had zero standoff (Figure 5-4). Cerro Alloy is an alloy with a low melting point (approximately 158°F), which is suited to this application because it is easily cast to conform to irregularities like weld beads or discontinuities that are exactly opposite the place where the charge would be detonated. This ability to conform allows the momentum plate to be in intimate contact with the test plate so that the shock wave reflected in the test plate is minimal and most of the shock passes into the momentum plate.

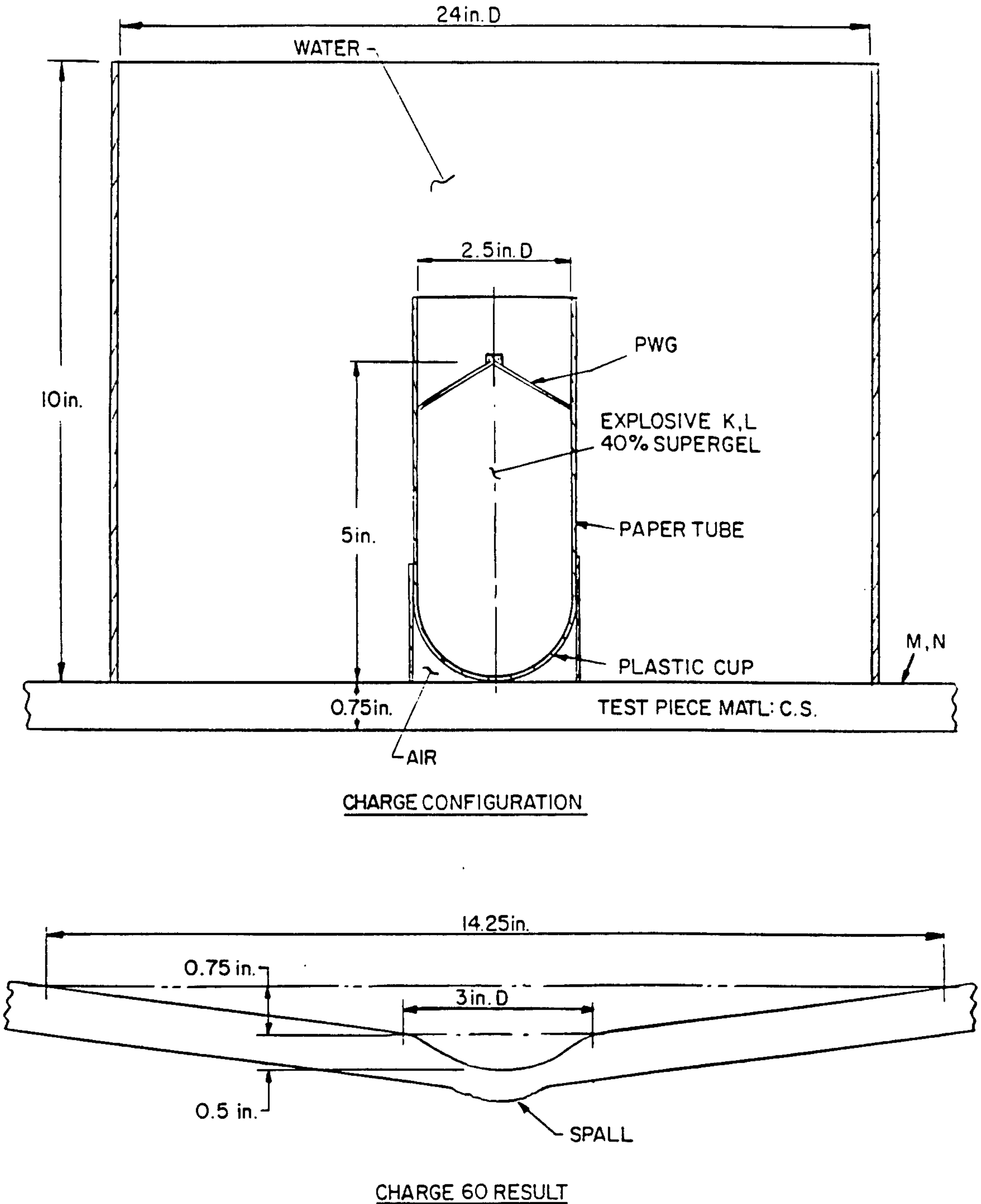


Figure 5-3. Solid Cylindrical Charge With Spherically Shaped End (Letters in illustrations are keyed to columns in Table 5-2.)

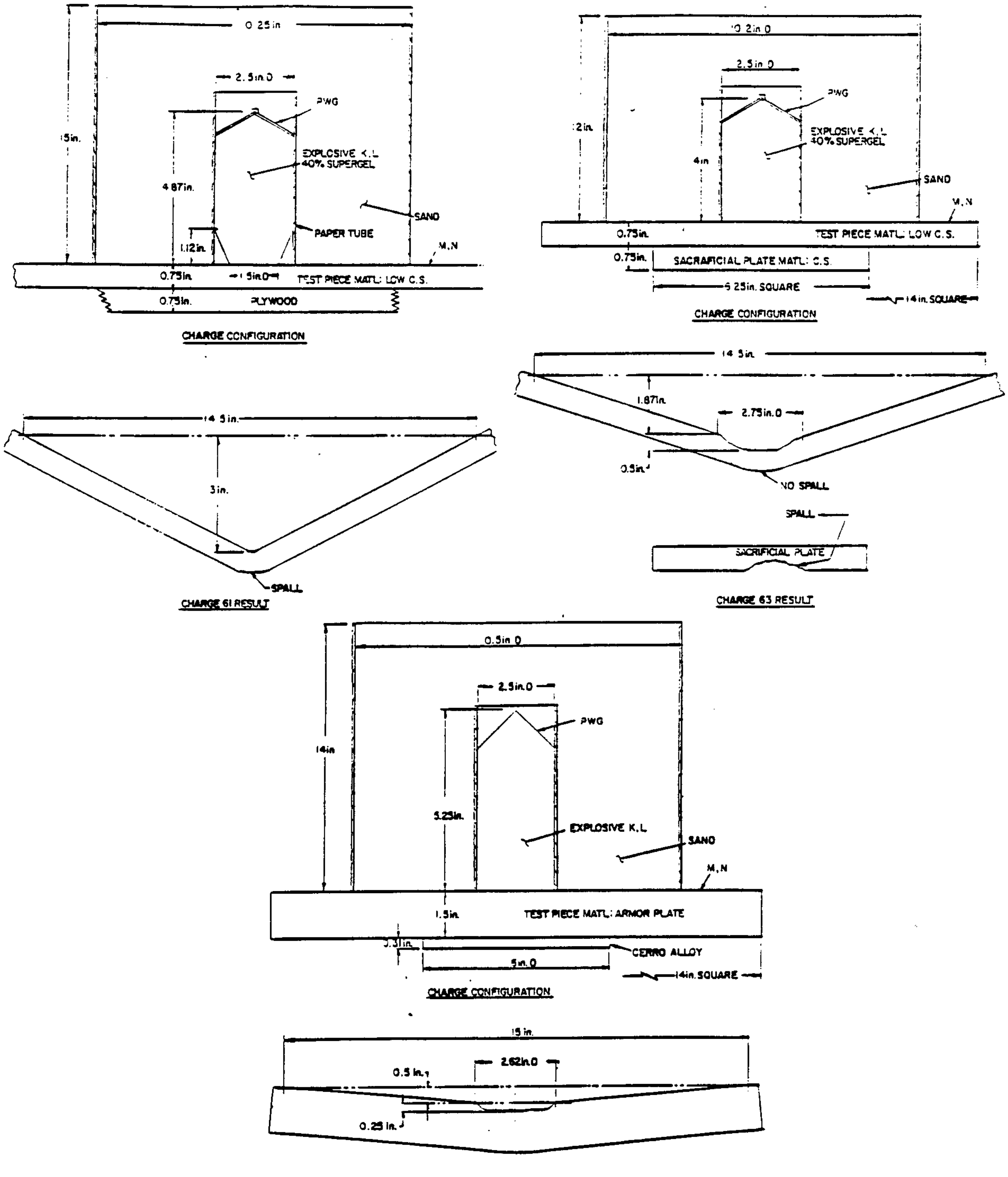


Figure 5-4. Typical Solid Cylindrical Charges With Various Momentum Plates (Letters in illustrations are keyed to columns in Table 5-2).

Results from Charge 61 showed that the inverted cone generated a conical depression but no dimple-like projectile impact in the center. The plywood did not protect the test plate back-side from spalling. Charge 63 developed a depression and dimple in the 0.75-in. plate very similar to the sample ballistic projectile impression in the test plate supplied by TACOM (Figure 5-4). The center dimple was 2.75 in. in D and 0.5 in. deep; the conical depression was 1.875 in. Although the momentum plate sustained some spalling, it protected the test plate from spalling. The test plate had no spalling on the face or back.

Charge 65 was detonated under 14 in. of sand on a 1.5-in. armor plate sample approximately 14 in. by 14 in. square with a Cerro Alloy momentum plate 0.313 in. thick held on the back with tape. No spalling or cracking of the face or back was noted. The depression was 0.5 in. deep.

Charge 66 was detonated under 14 in. of sand on the TACOM 1.5-in. armor plate sample approximately 36 in. by 36 in. (marked "scrap") with a 0.313-in.-thick Cerro Alloy momentum plate held to the back by tape. The charge was placed directly over the weld (Figure 5-5). No spalling or cracking of the face or back was noted after detonation. The depression was 0.3 in. deep. Since the required depth from the sample was from 0.88 to 1.7 in., a much larger charge was required. If length were added to a solid cylindrical charge, the length-to-diameter ratio would increase to more than 3:1.[9] Ratios over 3:1 do not significantly increase the charge energy at the target. Therefore, to increase energy at the target using more explosive, charge diameter would have to be increased. The result would be a larger dimple in the center of the depression than the one left by a projectile. Concentration of the energy from a larger diameter charge could be accomplished using a projectile. Continued testing explored the effect of projectiles.

5.4.3. Solid Cylindrical Charges With Projectiles. The third group was solid cylindrical charges with projectiles. The projectiles consisted of alternating layers of graded stainless steel disks and aluminum powder in Charges 34-37 and iron powder in Charges 38 and 40. These charges were based on the O'Keefe patent, which can be used without restriction for U.S. military applications.[6] It describes the process of using graded thicknesses of disks, starting with a mylar film disk, a layer of metallic powder approximately 0.03 in. thick, a thicker disk of stainless steel (approximately twice the previous thickness) with an alternating layer, similarly thick, of fine metallic powder (i.e., aluminum dust or iron dust). The thickness is gradually increased until the required mass or height is reached. The action of this charge, as described in the patent, is that the detonation shock accelerates the thin mylar plate, compressing the powder below it and increasing its temperature and pressure, thereby melting and vaporizing it. The vaporized material provides an effective accelerating medium for the next flat plate. When the shock passes, the melted and vaporized material solidifies, forming a weld between the two plates. This process is repeated as the shock wave passes through the set (plate and porous material)

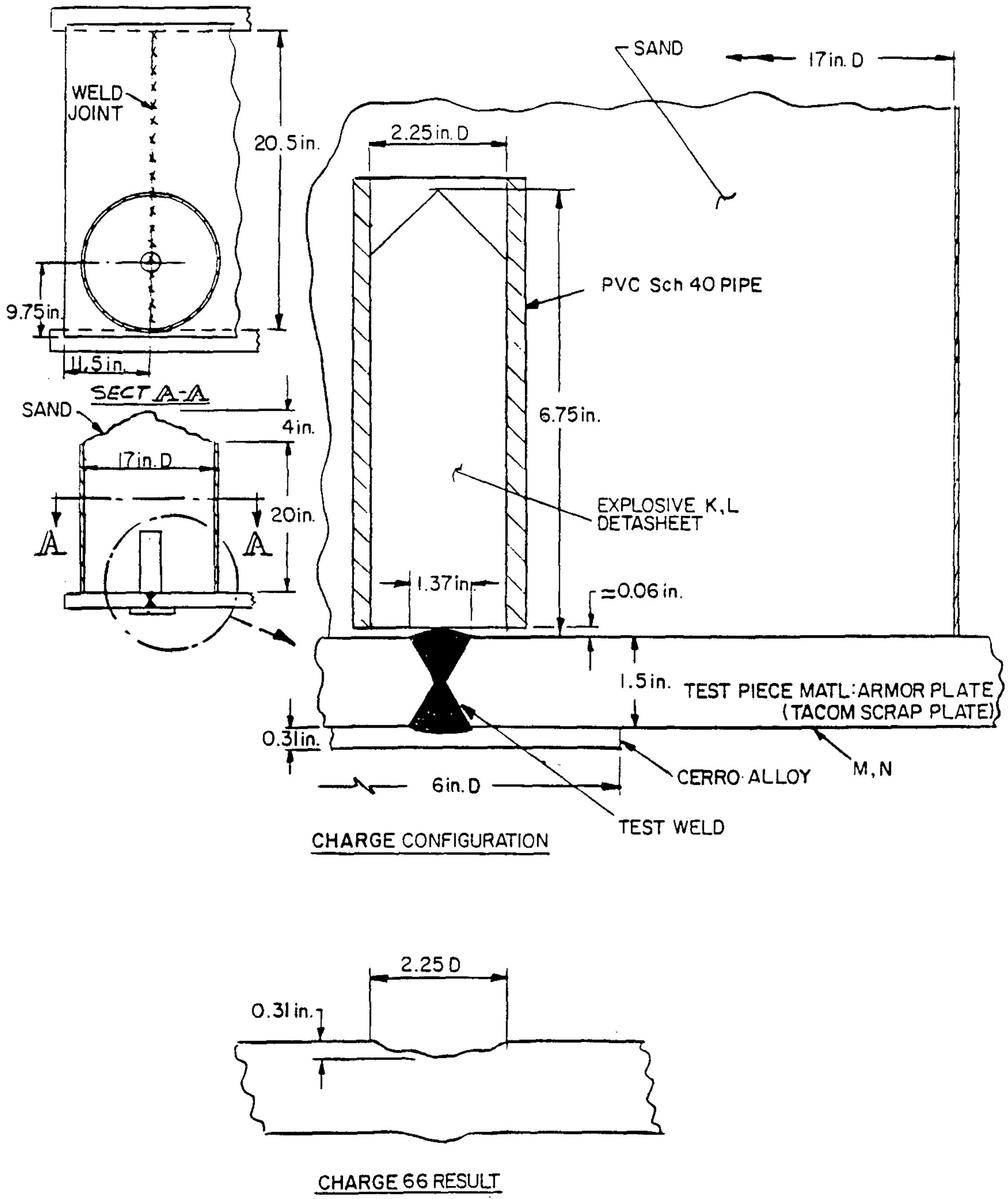


Figure 5-5. Solid Cylindrical Charge With Sand Containment and Momentum Plate on Armor Plate Weld (Letters in illustrations are keyed to columns in Table 5-2.)

until all the plates are accelerated as one mass and act as a projectile (Figure 5-6). The shock wave velocity is gradually reduced in the process to the sonic velocity of the projectile material.

Disks for these tests were 2-in.-D stainless steel (0.031, 0.063, 0.125, 0.25, and 0.375 in. thick). Nitroguanidine was used for Charge 34. Detasheet C was used in Charge 37. The remaining charges (35, 36, 38, and 40) used 40% dynamite. Charges 34 through 38 and 40 were a 2-in. Schedule 40 pipe approximately 7 in. high (Charge 24 was 7.75-in. high) into which alternating layers of metal disk and powder were placed so that the thickest disk was at the bottom and the thinnest was next to the explosive. Explosive filled the remaining pipe above the disks. A sheet of Detasheet was placed at the top to aid in detonating the explosive. The charges were placed on a 0.75-in., low-carbon-steel plate with 2-in. standoff and air in the interface. The total disk thickness, powder, charge size, explosive, and impression depth are given in Table 5-2.

These charges developed a conical depression with a circular impression approximately 2.125-in. in D at the center. The general form of this depression was very similar to that produced by a ballistic projectile, except that the maximum depth was 0.482 in. in 0.75-in., low-carbon steel. The depth required in each 1.5-in. armor plate sample was 0.875 to 1.69 in. A substantial increase in the power to accelerate the projectile and a heavier projectile were thus required. A longer charge was not practical; therefore, work was directed toward using larger diameter cylindrical charges with cylindrical cavities in an effort to concentrate more of the charge energy to accelerate the projectile.

5.4.4. Cylindrical Charges with Formed Cavities and Projectiles. These tests were conducted to devise a method for increasing charge size and accelerating a projectile without destroying it before it impacted upon the target plate. This group has been divided into eight configurations, based on projectile and cavity design. Detailed charge dimensions, figure numbers of typical charges, and results are given in Table 5-2.

The first configuration (4a) is Charge 16, which contained a 1.5-in.-D by 0.402-in.-thick stainless steel disk with a tight fitting ring (2.02-in. D) of similar material. The ring allowed the radially traveling compressive waves in the projectile, produced by its violent longitudinal acceleration, to propagate across the projectile disk-ring interface and reflect from the outer edge as a tensile wave. The rim-projectile interface could not sustain a tensile stress, thus the waves were trapped in the rim. The stress gradient and trapped waves tore the rim apart, and rim fragments project radially, leaving the projectile to proceed forward intact. The ring weighed 74 g and the disk was 80 g. The charge was 3.15 in. in D and 3.85 in. long, with a 2-in.-high truncated cone on top (3.15 in. in D at the face and 1 in. in D at the top). A cylindrical cavity 1 in. deep, with a 1.75-in. D, was at the

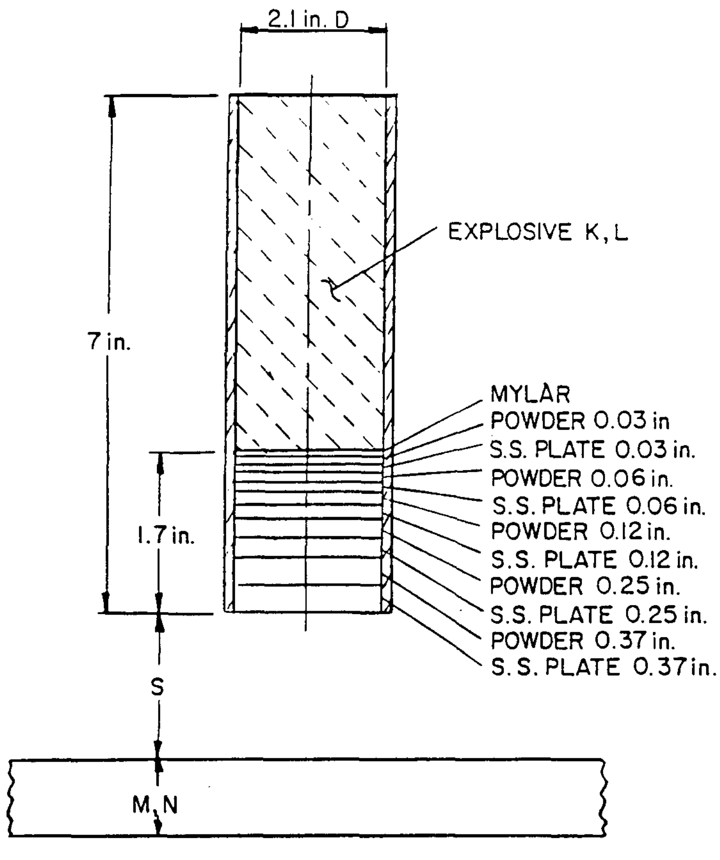


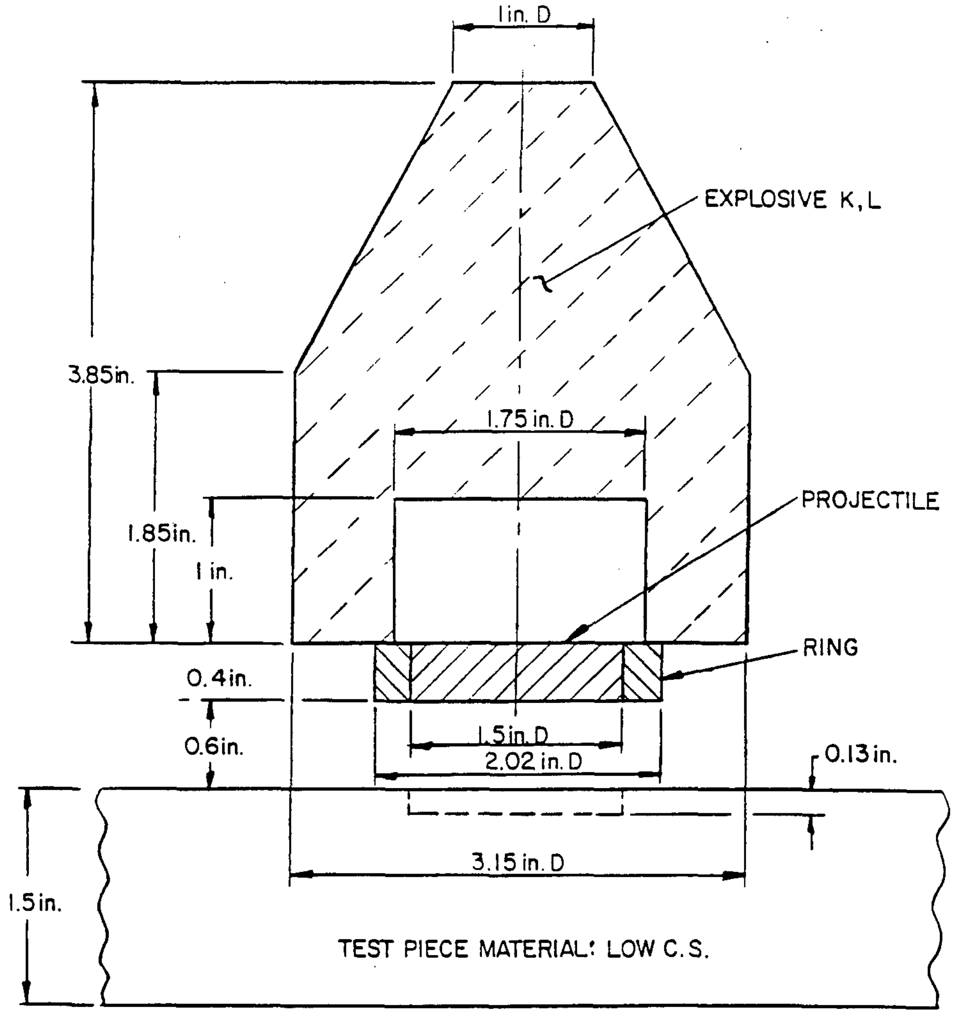
Figure 5-6. Typical Solid Cylindrical Charge With Layered Projectile (Letters in illustrations are keyed to columns in Table 5-2.)

bottom of the charge. The charge contained 254 g of Nitroguanidine explosive. The disk and ring were placed at the bottom of the cavity. The charge had a 1-in. standoff from the 1.5-in., low-carbon steel plate (Figure 5-7); it was detonated from the top. The result was a smooth dent in the plate (approximately 1.625 in. in D and 0.126 in. deep). No measurable plate deformation was noted.

Configuration 4b consisted of Charges 17, 18, and 19--charges with cylindrical cavities with disks placed in various locations in the cavity. These charges were identical except for the projectile and standoff distance. The basic charge was cylindrical with approximately 63 g of Detasheet C in a 1.125-in. in D tube, 2.5-in. long with an 0.875-in.-D by 1-in.-long cavity in the bottom. A PWG detonated the explosive uniformly across the charge. In Charge 17 a 0.25-in.-thick steel disk was placed in the bottom of the cavity (away from the main charge). The charge was placed on a 0.75-in., low-carbon steel plate with a 1-in. standoff. In Charge 18 a 0.25-in. disk was placed at the top of the cavity (next to the main charge); Charge 19 had a 0.5-in. disk at the top of the cavity. Charges 18 and 19 were placed on a steel plate with no standoff. These steel disks acted as buffers instead of projectiles. Charge 17 showed no depressions. Charge 18 had a flat depression approximately 0.025 in. deep with a jet spall 0.199 in. deep. Apparently, the charge jet penetrated the 0.25-in. disk. Charge 19 had a relatively flat dent approximately 0.875 in. in D by 0.149 in. deep.

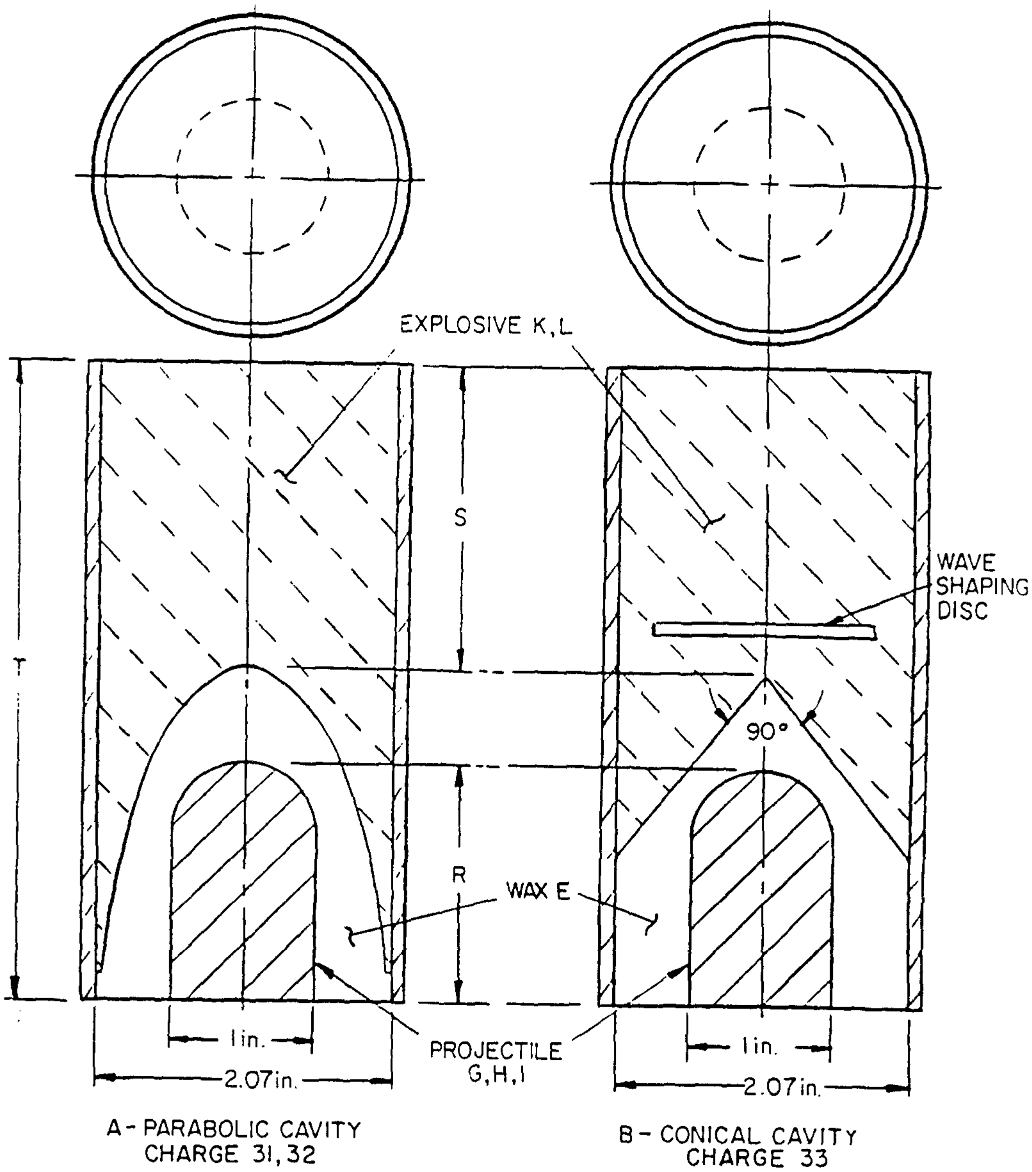
Configuration 4c (Charges 31-33) was suggested by the Bilek patent.[5] This patent is available for U.S. military use with no restrictions. In it a charge is described which uses a parabolic or conical cavity filled with wax to protect the projectile from the charge jet, which accelerates a steel cylindrical projectile with a spherical end (Figure 5-8). Charge 33 is a variation using a conical cavity with a detonation wave-shaping disk imbedded in the explosive [Figure 5-8 (b)]. These charges were constructed using Detasheet C explosive in a cylindrical container. Charge 31 contained 229 g (2-in. standoff), Charge 32 contained 241 g (3.5-in. standoff), and Charge 33 contained 293 g (12.25-in standoff). Charges 31 and 32 produced excessive jet spalling on the steel plate surrounding the projectile impact point; therefore, Charge 33 was moved farther away to the 12.25-in. standoff. Although a small indent was observed on the 0.75-in., low-carbon-steel plate target, the projectile appeared to have tumbled. Because the tumbling could not be controlled easily, work on this design was discontinued.

Configuration 4d was suggested by the work discussed in Section 5.4.3. (alternating layers of metal powder and disks, but with a larger charge). Charges 39 and 41-43 were designed to increase the total energy available. A larger diameter charge was constructed, and a cavity was used to improve energy concentration on the projectile. The projectile stacks (described in Section 5.4.3.), containing iron powder and stainless steel disks, were installed in the cavities.



CHARGE 16

Figure 5-7. Cavity Shaped Charge With Ring-Protected Disk Projectile (Letters in illustrations are keyed to columns in Table 5-2.)



CHARGE	R	S	T
31	1.98in.	1.46in.	5.0in.
32	2.02in.	1.49in.	5.1in.
33	3.04in.	1.47in.	5.0in.

Figure 5-8. Cylindrical Charges With Shaped Cavities and Shaped Projectiles (Letters in illustrations are keyed to columns in Table 5-2.)

In Charge 39, the charge diameter was increased to 3.5 in.; it was approximately 8.125-in. long with a 2-in.-D by 3.7-in.-deep cylindrical cavity. The layered stack of disks was placed into the top of the cavity next to the explosive, 1459 g of 40% dynamite (Figure 5-9). The charge was set on a 0.75-in. steel plate and detonated with a PWG. The result was a through hole caused by the compression of gases between the projectile and the plate. The charge "skirt," which surrounded the cavity below the charge, formed a jet which was compressed by the projectile stack, penetrating the test plate.

Charges 41 and 42 were similar, 4 in. in D by 7.25 in. long, with 2-in.-D by 3.025-in.-long cavities respectively. The layered disk stacks were placed on the 0.75-in. steel test plate. The charges had no standoff. They were detonated with a PWG placed on top. The plate was fractured in both tests, with spalling apparent on the plate back directly under the charge.

Charge 43 was similar to Charges 41 and 42 except it was 0.5 in. longer with a 0.5-in.-longer cavity filled with wax. Both layered projectile and charge were placed on a 1-in., low-carbon-steel plate with no standoff. The layered projectile was fractured by the detonation wave, and only the debris contacted the test plate, forming multiple but minor indents.

Configuration 4e consisted of six charges (44 through 49)--a cylindrical explosive with a cylindrical cavity filled with wax and a stainless steel projectile. Based on a discussion in the Bilek patent, wax was used in the cavity.[5] The patent said that the detonation wave causes the wax to vaporize, increasing the mass and effective pressure on the projectile for a longer time, thereby increasing its impulse. The wax also reduces the shock wave velocity, protecting the projectile from the destructive shock. Figure 5-10 shows a typical charge; Table 5-2 lists charge parameters.

Charges 44-47 were almost identical; standoff distance was one difference. They consisted of cylindrical explosives (40% dynamite) 3.3 in. long, 4 in. in D. The cavities were cylindrical, with a 3.1-in. D, 1.3 in. deep, filled with wax. The projectiles were stainless steel disks 2.3 in. D, 0.5 in. thick, weighing approximately 243 g. A PWG detonated the charges.

Charge 48 was larger, 4.4 in. long with a 5.3-in. D, a cylindrical cavity (4 in. in D by 1.5 in. deep) filled with wax, and a 3.5-in.-D by 0.88-in.-thick stepped stainless steel disk projectile. Charge 49 had a 5.3 in. D and was 5 in. long. It had the same cavity as Charge 48, with a 3.5 in. D by 1.4-in.-thick stepped disk. The disk step simulated the diameter of a 75-mm projectile.

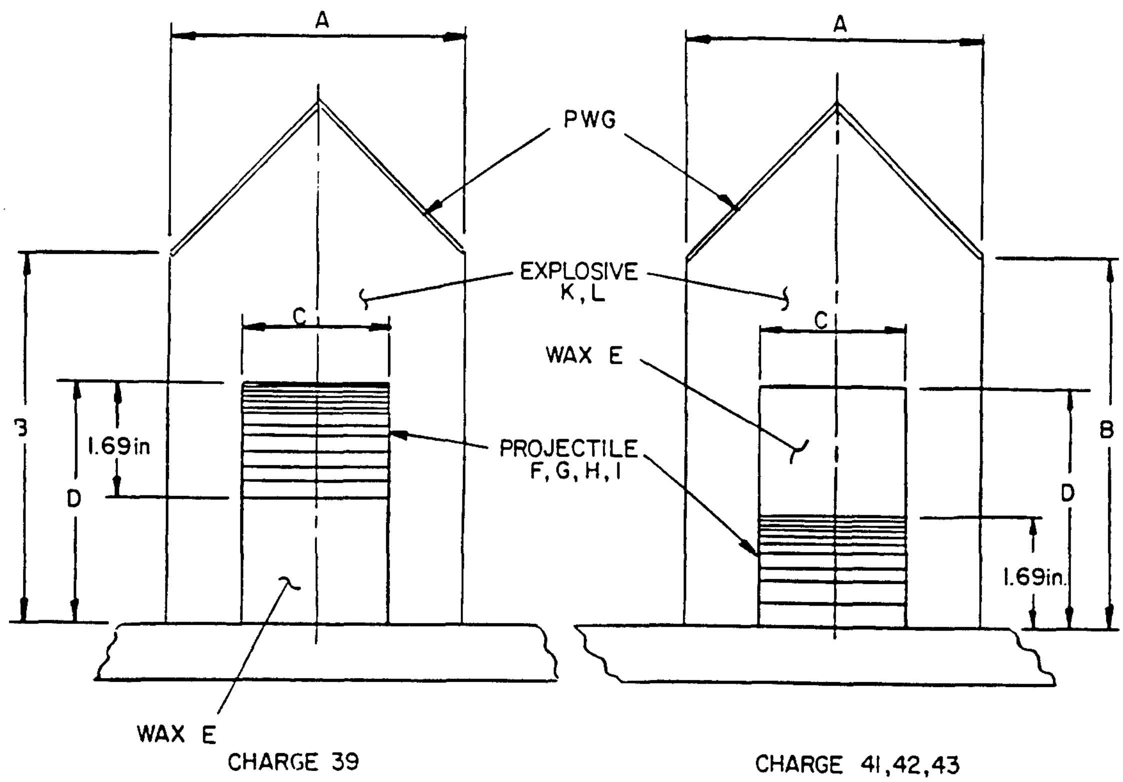


Figure 5-9. Typical Cylindrical Charge With Cylindrical Cavity Containing Layered Projectiles

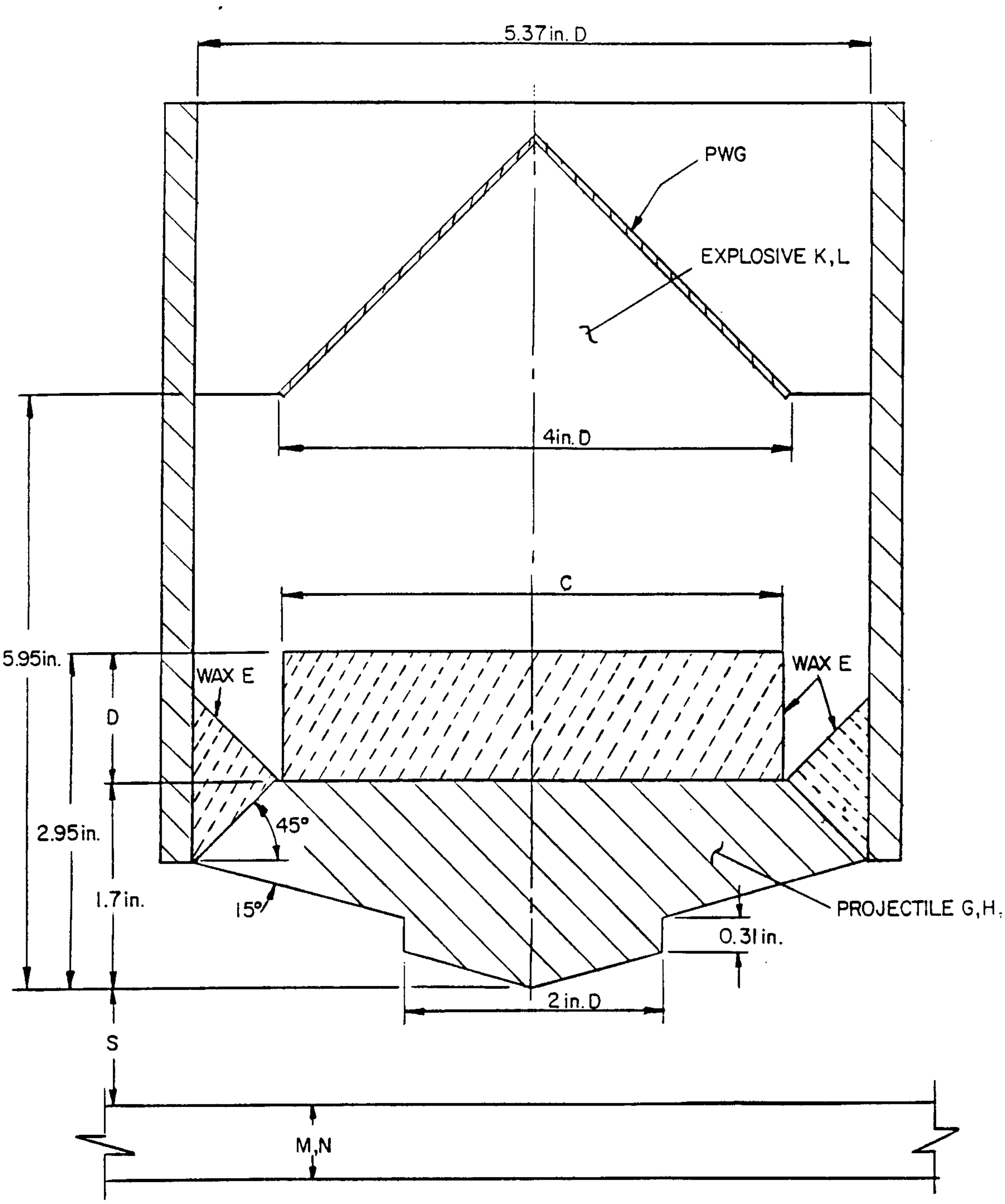


Figure 5-10. Typical Cylindrical Charge With Cylindrical Cavity Containing Wax Buffer and Shaped Solid Projectile (Letters in illustrations are keyed to columns in Table 5-2.)

Standoff distances (with air in the interface) were: none, 1, 2, 0.5, 1, and 1 in. for Charges 44 through 49, respectively. All were detonated on a 1-in., low-carbon steel plate supported on 2- to 3.5-in.-D steel bars, 12 in. on centers.

Charge 44 produced back-side spalling. The remaining charges (45 through 49) had no back-side spalling, but had hot gas jet erosion around the projectile impact area resulting from the portion of the jet that bypassed, and was compressed by, the projectile. The charges produced conical depressions in the 1-in. test plate as follows:

- 44 - 1.13 in.
- 45 - 1.06 in.
- 46 - 1.19 in.
- 47 - fractured the plate
- 48 - 2.4 in.
- 49 - 1.9 in.

These depressions were similar to the TACOM test plate samples.

Configuration 4f, consisting of Charges 50-52, was based on the depressions generated by Charges 44 through 49. Those depressions were similar to the TACOM sample supplied, but they were formed on 1-in., low-carbon steel plate. To form the required depressions in 1.5-in. armor, charge size had to be increased and jet spalling on the face eliminated. A projectile was made with a beveled ring around its outside diameter to deflect gases laterally. The lower end of the projectile was formed to aid in expelling the air in the cavity formed by the standoff.

Charges 50-52 were very similar and had a shaped stainless steel projectile. Each was 5.5 in. long and had a 5.3-in. D; each had a 1.3-in.-deep cavity (with a 3.8-in. D) filled with wax. A wax ring was also installed on the projectile bevel. The charge was detonated with a PWG. Charge 50 was tested on a 1-in., low-carbon-steel plate with a 1-in. standoff. Charges 51 and 52 were tested on a 14- by 14- by 1.5-in. armor plate with a 2-in. standoff. The armor plates were supported on 5- by 5-in. steel bars spaced 13 in. apart on all four sides. Charge 50 on 1-in., low-carbon steel plate resulted in a 1.63-in. conical deflection with a central depression 0.5-in. deep with a 2.5 in. D. For Charge 51, the conical depression was 0.16 in.; for Charge 52, 0.14 in. on 1.5-in. armor plate. No face or back-side spalling was noted. The projectiles for Charges 51 and 52 flattened into a smooth saucer shape. A much harder projectile is required.

Configuration 4g, Charge 54, was a cylindrical charge 3.63 in. long with a 7.13-in. D; the cavity was 1.5 in. deep with a 5.3-in. D. It was loaded into a carbon-steel pipe with 0.75-in.-thick walls. The projectile consisted of a 1.5-in.-thick armor plate disk (7.2-in. D) with a smaller 2.25-in.-D by 1.5-in.-long armor plate material disk tack welded to it to simulate projectile diameter. The centerlines of both disks were coincident. This charge was detonated on a 1.5-in. armor plate sample approximately 14 by 14 in. square supported 12 in. on center by 3.5-in.-D bar stock.

The resultant conical depression was 2.37 in. deep, with an almost spherical depression in the center of the conical depression. This shape of depression occurred because the projectile, consisting of two 1.5-in. armor plate disks, flattened into a pie-shaped plate (Figure 5-11). No face or back-side spalling was noted. This test was very encouraging, based on the deformation results. The charge size used, approximately 3,950 g of 40% dynamite, would not be allowed as a surface shot in most locations. The heavy steel pipe concentrated and directed the charge energy, but generated considerable shrapnel, which in this case was contained in a test enclosure. Additional explosive would be needed to develop a charge that would eliminate the heavy pipe.

5.5. Review Results of Task 2 and Determine Test Configurations (Task 3)

Three explosives and four basic charge techniques were demonstrated in Task 2--each with a number of variations. Generally, the low-velocity/low-density explosive, Nitroguanidine, did not supply sufficient energy to be useful. The high-velocity explosive, Detasheet C, proved very expensive, and the high-velocity shock was difficult to attenuate; therefore, plate spalling occurred. The 40% dynamite generated an adequate amount of energy at a relatively low velocity, was inexpensive, was easily procured in small quantities and easily formed. Therefore, most of the testing was conducted using this explosive.

The first group of tests was conducted with simple cylindrical charges with cylindrical cavities. Some were modified with plastic liners, copper flyer plates, and powdered iron for flyer material. Face spalling occurred during all tests. It was caused by a hypervelocity jet of material, which impinged upon the test plate, penetrated the plate, and ejected the molten material formed by the extremely high pressure and jet velocity. There was no indication of any plate deformation in these tests.

In the second group of tests, the effect of solid cylindrical charges used directly or with standoffs and the effect of charge confinement and buffer material between charge and test plate were studied. In this case the detonation pressure wave, which could reach 1 million$^+$ psi, was directed to the test plate. The charge directly on the plate caused local deformation directly under the charge and spalling on the back of the test plate. When modifying buffers such as air, water, and polyethylene were added and the charge was moved away from the test plate (standoff), local deformation changed into a spherical depression similar to the that in the Navy bulge test.

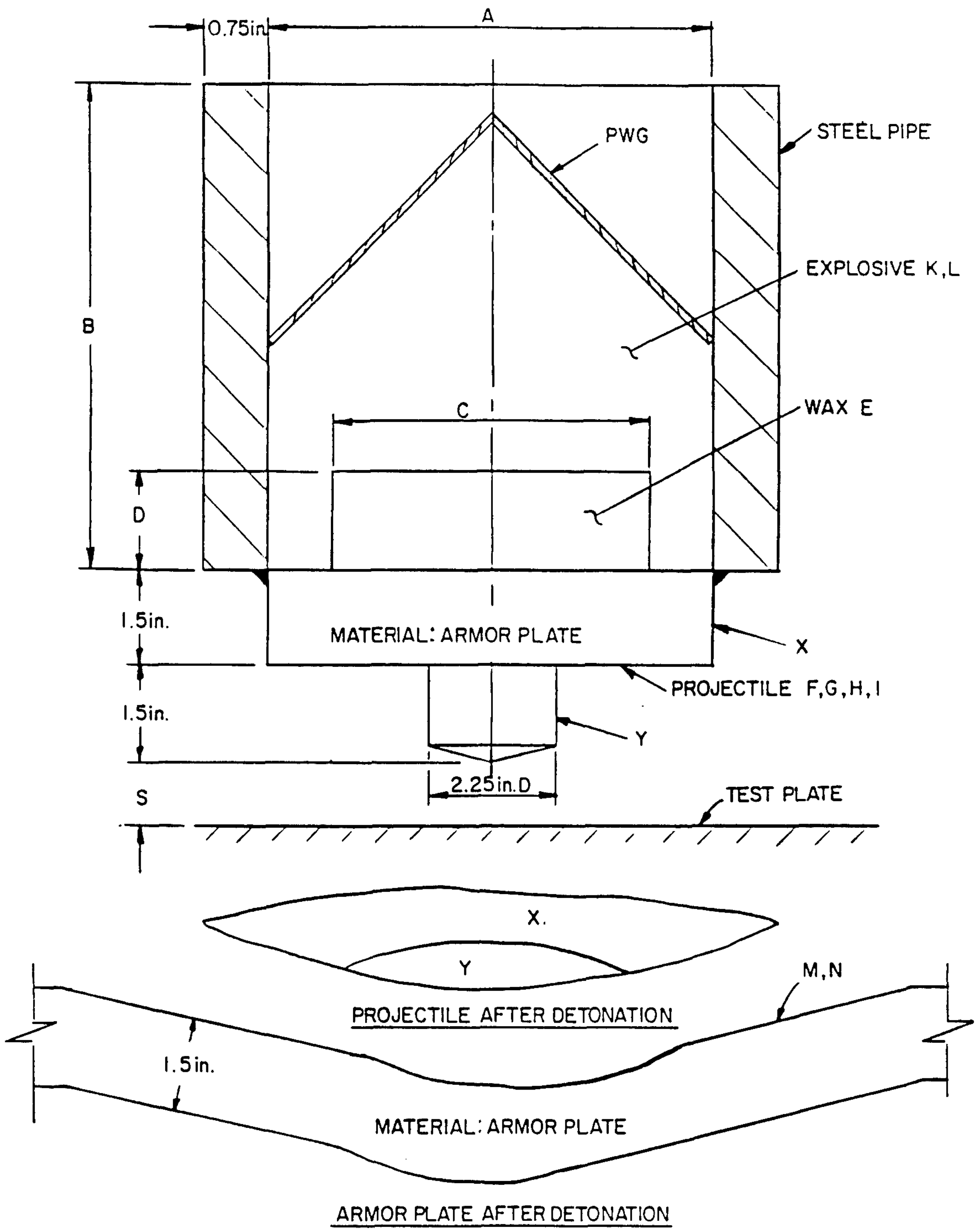


Figure 5-11. Solid Cylindrical Charge With Cylindrical Cavity Containing Wax Buffer and Projectile Made From 1.5-in. Armor Plate (Letters in illustrations are keyed to columns in Table 5-2.)

In the third group of tests, a buffer and disks were added to form a projectile. The high detonation pressure caused the metallic powder layered between disks to vaporize, developing a high vapor pressure to accelerate the disks.[6] When the shock passed, the molten and vaporized powder solidified, welding the two adjacent disks together. This action was repeated in each layer, slowing the detonation wave while accelerating the layered disk projectile. Results on low-carbon steel plate were encouraging, but a charge sized for the 1.5-in. armor plate was not practical because the charge diameter had to be maintained to the projectile diameter. An increase in the charge length to more than three times the diameter was not effective in increasing the projectile energy at the test plate.

The fourth group of tests was conducted to investigate various ways of concentrating the energy of larger diameter charges to develop an imprint similar to a projectile. A number of variations of two methods were explored. The first was using shaping cavities--parabolic, conical, and cylindrical--along with a buffer material (wax) in the cavities. These concentrated jets accelerated the projectile which impinged upon the plate. The projectile shape was also changed to present a larger area to the charge pressure. The opposite side of the projectile had a cylinder simulating the diameter of the 75-mm projectile. The charge and projectile were modified to reduce the chance that the high-pressure combustion products of the charge would enter under the projectile and be compressed, causing the target to erode.

The charge style selected was similar to Charge 54. The projectile presented a large area to the charge pressure pulse and was protected with a 1.38-in. layer of wax. Two diameters were selected (5 and 6 in.). The 5-in.-D charge had a very strong, compact, shaped projectile, but it was limited by the quantity of explosive that could be used because of the 3:1 length-to-diameter limitation.[9] This charge size was marginal for generating the maximum 1.69-in. depression. Therefore, a 6-in.-D charge was also selected. The projectile consisted of two pieces: A large 6-in.-D piston approximately 1.38-in. thick and a cylindrical, tapered piece to simulate the ballistic projectile. Figures 5-12 and 5-13 show the typical test setup with 5-in. and 6-in. final charge configurations.

5.6. Sizing Tests of Selected Charges for Comparison Tests (Task 4)

Twelve charges were fabricated, four 5-in. charges, as shown in Figure 5-12, and eight 6-in. charges, as shown in Figure 5-13. Of these twelve charges, eight were to be tested during Task 4. (A discussion of testing of the remaining charges is presented in Section 5.8--Test of Full-Sized Weld Test Plates).

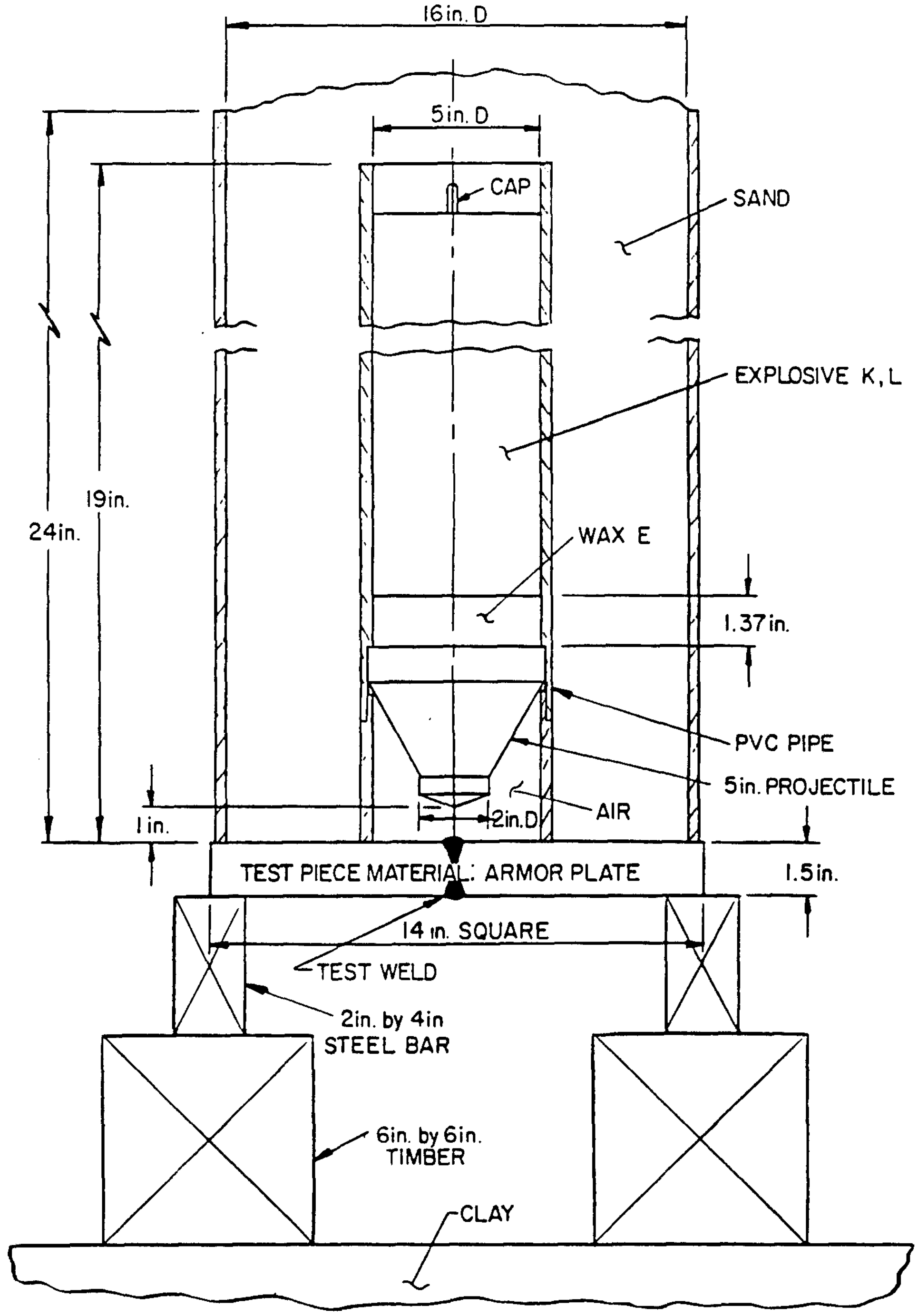


Figure 5-12. Typical Test Setup with 5-in. Final Charge Configuration (Letters in illustrations are keyed to columns in Table 5-2.)

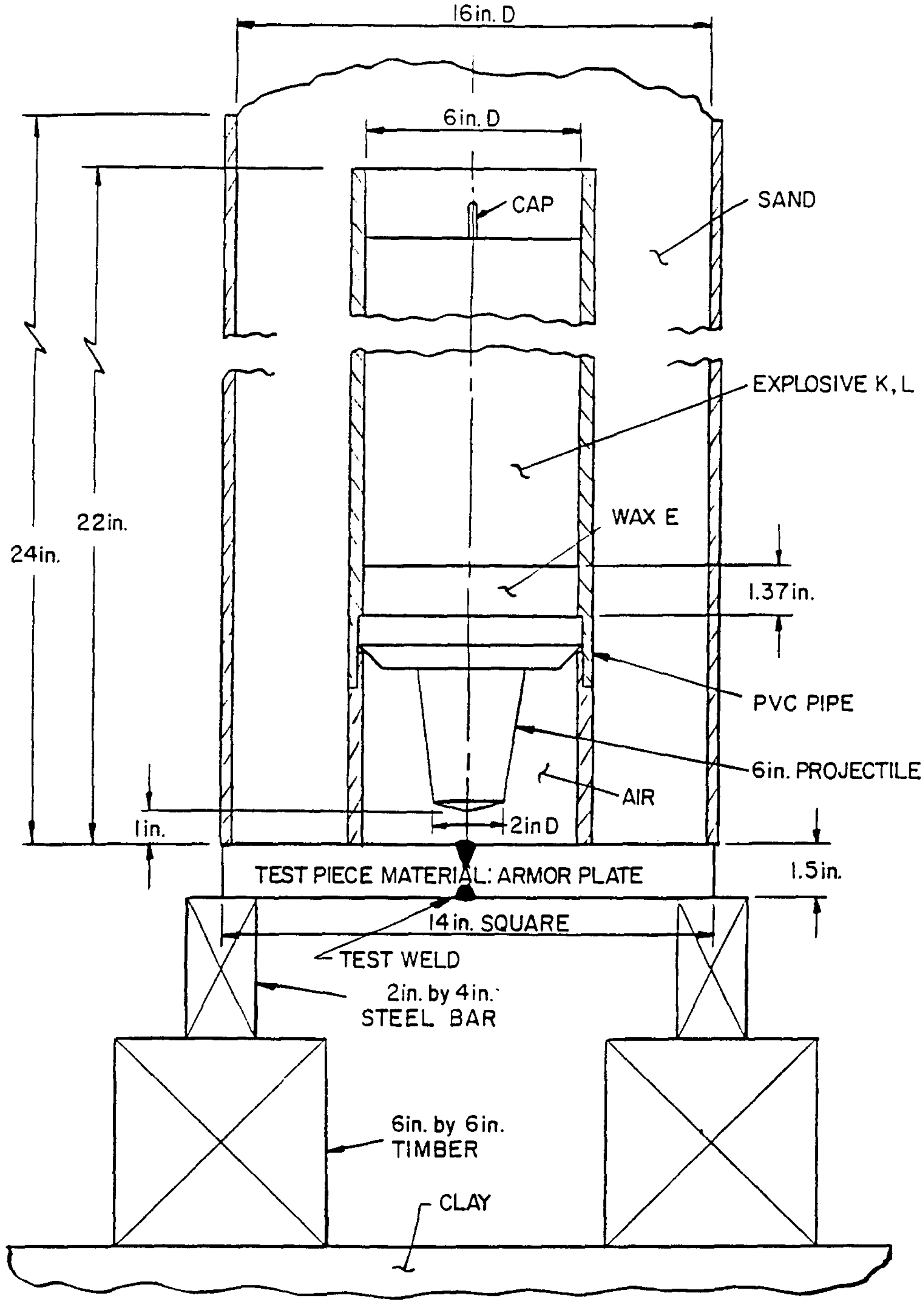


Figure 5-13. Typical Test Setup with 6-in. Final Charge Configuration (Letters in illustrations are keyed to columns in Table 5-2.)

Eight armor steel test plates (14- by 14- by 1.5-in.) were also fabricated with a double "V" 60-deg through plate weld in the plate center for its entire 14-in. length. The weld was made using the shielded-metal-arc welding method with Hoballoy 10018M (AWS E 10018M) electrodes from both sides, similar to MIL-STD-1941(MR), Procedure 1, Joint A-A.[9,1] All welds were visually inspected for cracking.

The estimated charge size for the minimum conical depression (0.875 in.) was approximately 4,540 g of 40% dynamite; for the maximum conical impression (1.700 in.), it was 6,810 g. Charges of this magnitude could not be detonated at our facility in Livingston, New Jersey. Therefore, arrangements were made to perform testing under Task 4 (eight sizing shots) at Explosive Fabricators in Louisville, Colorado. The 14- by 14- by 1.5-in. test plates, 6-in. charge assemblies, and 5-in. charge assemblies, along with the two 36- by 36- by 1.5-in. weld test plates supplied by TACOM, were shipped to Explosive Fabricators. Explosive Fabricators supplied all explosive (40% dynamite and T200W), caps, timbers, and steel bar blocking to support the test plates during testing.

Initial testing was scheduled for 5 May 1987, but it was postponed because of the weather. On 18 May 1987, these eight tests were conducted using the 14- by 14- by 1.5-in. welded test plates.

5.6.1. Charge Description (5-in.-D charge). Each charge housing assembly was made from two pieces of 5-in. Schedule 40 PVC pipe. The lower 2.2 in. of the upper housing was recessed to accept the projectile. The lower piece of PVC pipe was turned down to fit into the recess and capture the projectile.

Four longitudinal cuts were made in the recess and turned-down portion of each piece of PVC housing as crack starters. The length of the lower PVC pipe piece when assembled with a projectile provided a 1-in. standoff distance between the projectile and test plate. The projectile for the 5-in. charge consisted of SAE 4340 round bar material (5.25 in. in D) machined to a truncated cone with a short cylindrical section at the base approximately 1 in. long and a cylinder (2-in. in D) on the opposite end approximately 0.75 in. long to represent the 75-mm projectile nose. This projectile weighed about 6,810 g and was heat treated to give a Rockwell C in the mid-40 range. This range of hardness in 4340 material gives excellent toughness.

At assembly, the two PVC pipe pieces were cemented with the projectile captured between them. Molten beeswax (1.38 in. deep) was poured on top of the projectile, and the selected quantity and type of explosive was added above the beeswax (Figure 5-12).

5.6.2. Charge Description (6-in.-D charge). The charge housing was constructed identically to the 5-in. charge except with 6-in. Sch 40 PVC pipe. The projectile consisted of a two-piece assembly. The top section was a 6.25-in.-D disk approximately 1.375 in. thick, with a tapered cylinder tack welded to the bottom to represent the ballistic projectile. This assembly weighed about 6,810 g, approximating the weight of the ballistic projectile (Figure 5-13).

5.6.3. Test Setup (for Both 5- and 6-in. charges). A measured amount of the selected explosive was then installed (Table 5-3). A 0.08-in. layer of Detasheet C was placed on top of the explosive. This assembly was then placed on a test plate supported by four 2- by 4-in. steel bars. The detonating cap was placed atop the explosive, and a 16-in.-D by 24-in.-high cylinder of sand was placed around the charge to concentrate and direct the explosive energy. The charge was then detonated. (Figure 5-14 shows a typical setup.) Results of the initial eight tests are presented in Table 5-3. The table lists charge identification, charge parameters, setup parameters, measurement of conical deflection, maximum length of crack on back of plate, and noise measured in decibels 1,300 ft from detonation. Figures 5-15 through 5-18 are photographs of the test plates after testing, showing top depressions and back-side cracks.

5.7. Evaluation of Eight Sizing Tests and Four Comparison Tests (Task 5)

Evaluation of the eight tests conducted on 14- by 14- by 1.5-in. welded armor plate test specimens using five 6-in.-D and three 5-in.-D charges indicated that 3,632-g charges were required for the minimum depression (0.875 in.) and 6,356-g charges were required for the maximum depression (1.69 in.). These explosive weights were determined from a plot of results shown in Figure 5-19, where explosive charge size is correlated with depression depth. A least-squares fit curve was drawn through the data to determine the charges required.

The measurement of depression depth was made from the bottom of a 14.5-in.-long straight edge to the base of the depression dimple. The length of the straight edge was arbitrarily selected to be the standard for all measurements made for this program. This value was plotted with the equivalent charge weight on Figure 5-19. A least-squares fit line was determined for the initial eight tests using both the 5- and 6-in. charge results. An equivalent weight for the 5-in. charge was used so that both charges could be plotted on the same basis. This equivalent charge size ignored the additional impulse from larger diameter charges resulting from a longer period pressure pulse, considering only the differential areas of the two projectiles. Both 5- and 6-in. projectiles were approximately the same weight. The equivalent charge size, plotted in Figure 5-19, was determined as follows:

Equivalent charge size =

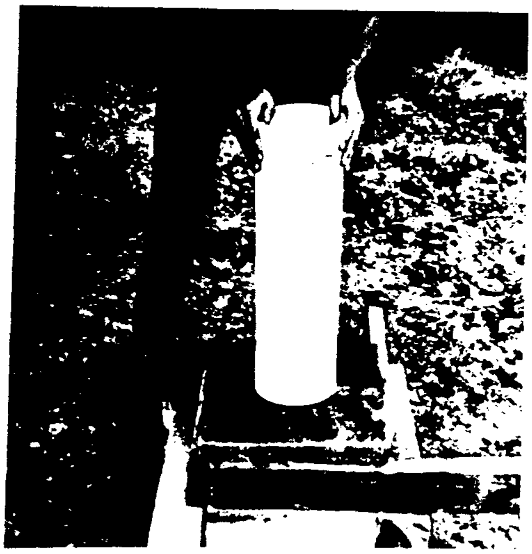
$$\frac{(\text{Weight of 5-in. charge explosive})(\text{Area of 5-in. charge explosive})}{(\text{Area of 6-in. charge explosive})}$$

Table 5-3. Sizing and Demonstration Tests[1]

Test Charge	Housing I.D.	Typical Figure	Projectile		Wax Buffer Material (g)	Explosive		Test Plate					Sound Level		Remarks
			Weight (g)	Hardness (R_C)		Type	Weight (g)	Size (in.)	Temperature (°F)	Dent Depth (in.)	Top Crack (in.)	Bottom Crack (in.)	Peak (dB)	Average (dB)	
1	G-6	---	6653	42	473	40%D	4767	14 by 14	80	1.3	---	---	138	130	Fractured
2	B-5	5-16A 5-21	6861	41	358	40%D	4082	14 by 14	86	0.78	---	6.6	138	130	
3	F-6	5-15 5-16B	6662	43	460	40%D	4082	14 by 14	87	1.23	---	3.3	130	120	
4	D-5	5-17A 5-25	6876	46	357	T200W	2268	14 by 14	77	0.28	---	1.4	---	---	
5	C-5	5-17B	6882	49	337	40%D	5443	14 by 14	82	0.6	---	2.5	143	135	
6	E-6	5-18A	7035	50	470	40%D	4463	14 by 14	80	1.13	---	3.8	139	131	
7	H-6	5-18B	6665	42	488	T200W	4763	14 by 14	78	1.0	---	5.2	(2)	(2)	
8	I-6	5-14 5-15	6645	38	495	40%D	4763	14 by 14	78	1.15	---	---	(2)	(2)	Fractured
9	J-6	5-21 5-22	6651	45	468	40%D	5897	36 by 36	77	0.8	16	24	---	---	
10	A-5	5-21 5-22	6936	45	384	40%D	5443	36 by 36	78	0.12	---	---	(3)	(3)	
11	L-6	5-21 5-23	6606	44	470	40%D	6804	36 by 36	78	0.75	---	---	(3)	(3)	
12	K-6	5-21 5-23	6660	40	469	40%D	8165	36 by 36	72	0.75	---	5.88	139	133	

1 All tests were conducted using a 16-in.-D by 24-in.-high sleeve (approximately 3 ft^3) full of sand to contain and concentrate the charge.
2 Tests 7 and 8 detonated together--total explosive charge = 9526 g; sound level: peak = 145.5 dB, average = 138 dB.
3 Tests 10 and 11 detonated together--total explosive charge = 12,247 g; sound level: peak = 147.5 dB, average = 140 dB.

(a) 1.5-in. Armor Steel Test Plate Shown on Steel Bars and Timber



(b) Placing Charge Over Weld on Test Plate

(c) Charge Ready for Detonation Showing Sand Containment Around Charge

(d) Results of Charge 8

Figure 5-14. Typical Test Setup for Charge Sizing Tests (5- and 6-in. Charges)

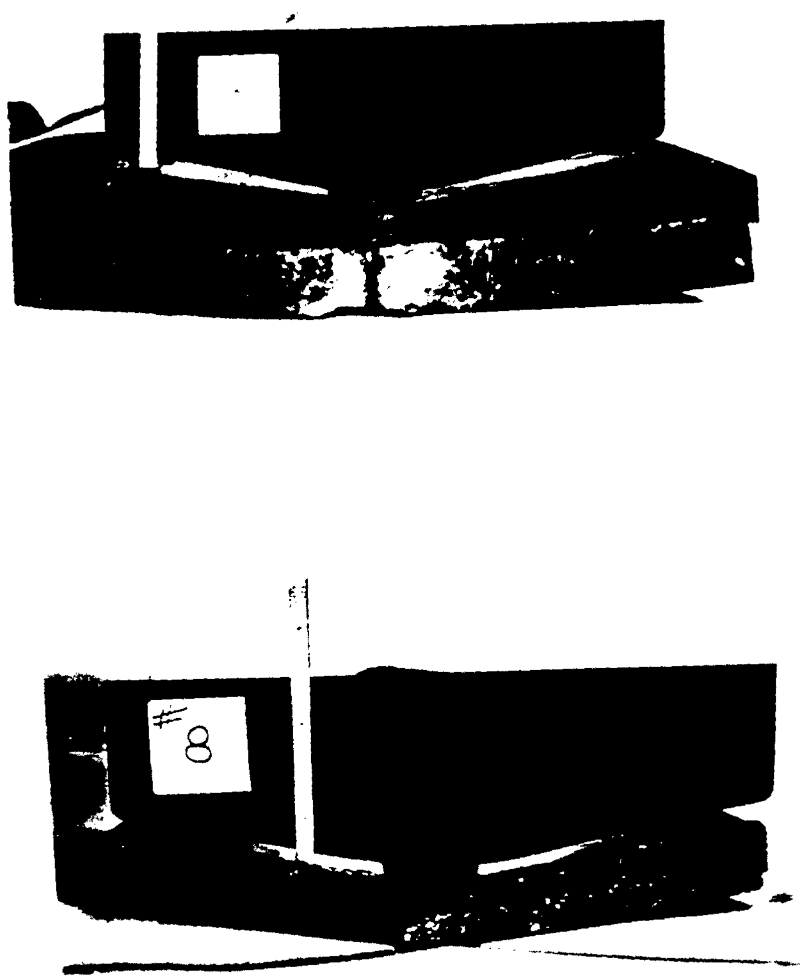
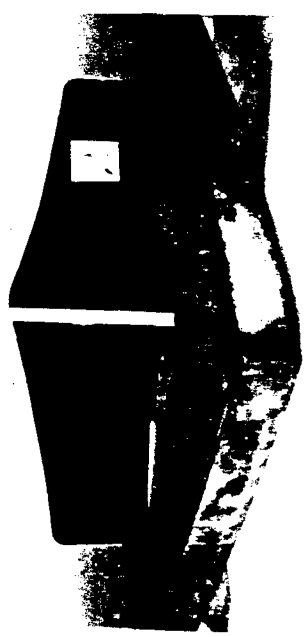


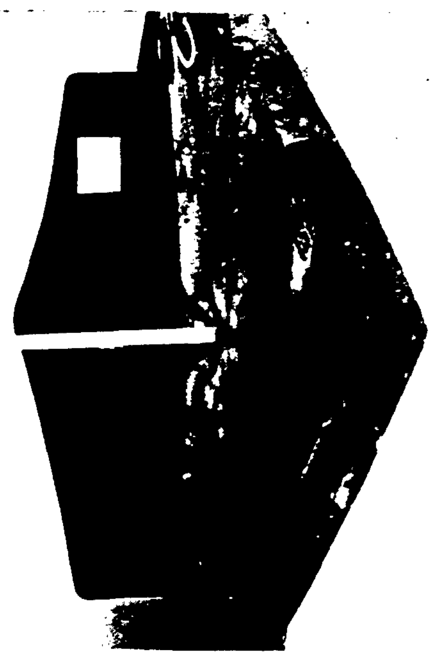
Figure 5-15. Test Charges 3 and 8 Showing Comparison of Projectile Impression to Template Made of TACOM Weld Test Plate Sample With Deeper Impression

Bottom of Plate With Visible Cracks Indicated by Marker

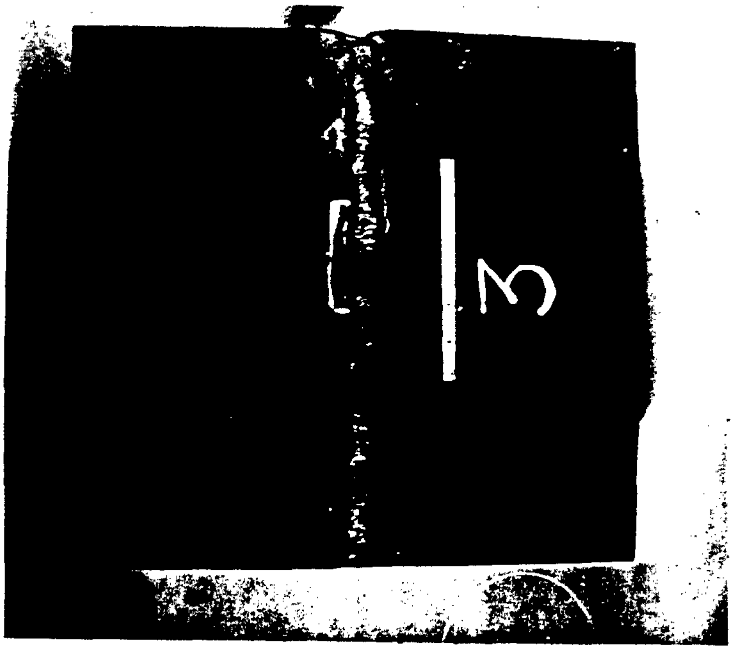


Top of Plate Showing Method of Measuring Dent

Figure 5-16a. Weld Test Plate Condition Following Testing (Test Charge 2)

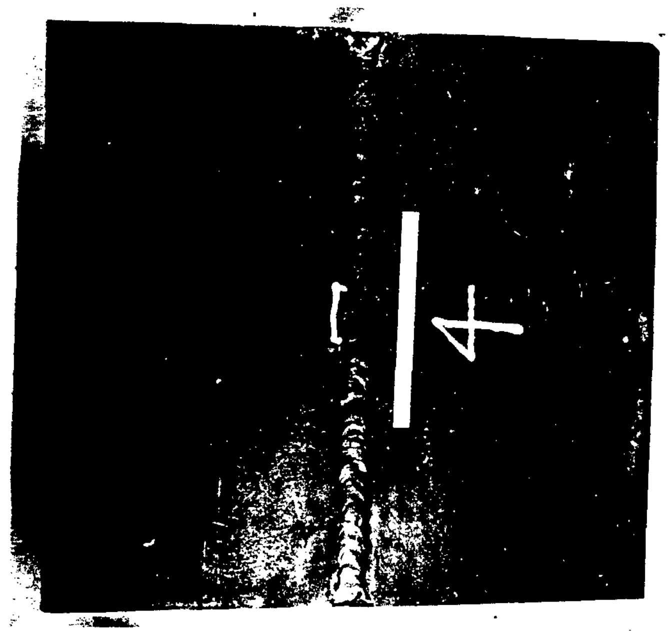


Top of Plate Showing Method of Measuring Dent

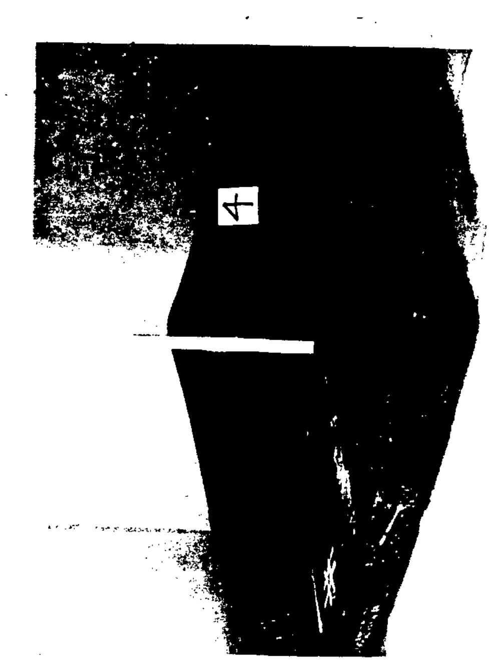


Bottom of Plate With Visible Cracks Indicated by Marker

Figure 5-16b. Weld Test Plate Condition Following Testing (Test Charge 3)



Bottom of Plate With Visible Cracks Indicated by Marker



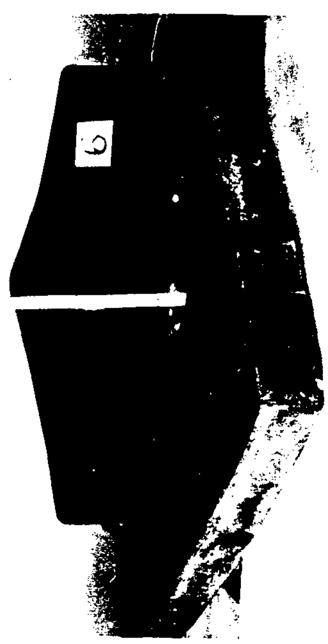
Top of Plate Showing Method of Measuring Dent

Figure 5-17a. Weld Test Plate Condition Following Testing (Test Charge 4)

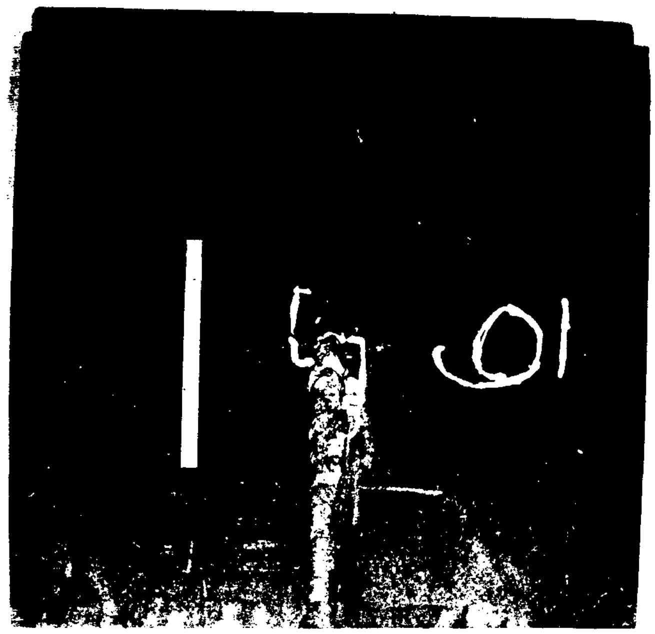
Bottom of Plate With Visible Cracks Indicated by Marker

Top of Plate Showing Method of Measuring Dent

Figure 5-17b. Weld Test Plate Condition Following Testing (Test Charge 5)

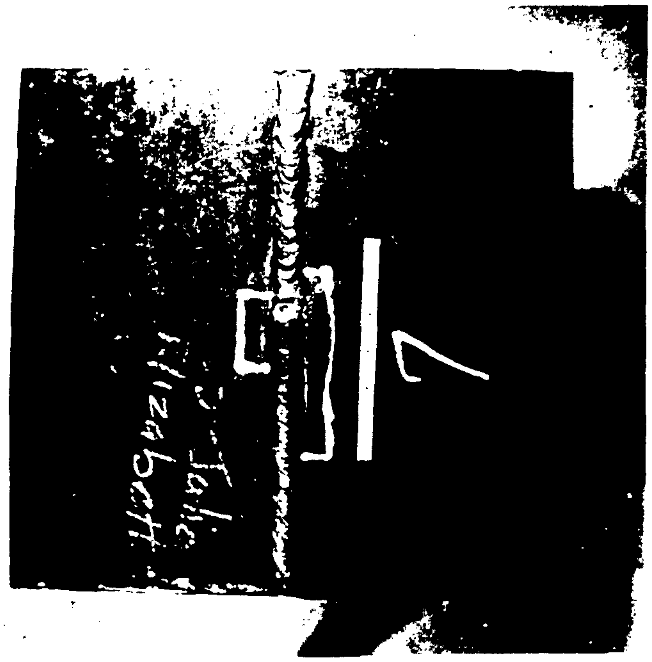


Top of Plate Showing Method of Measuring Dent

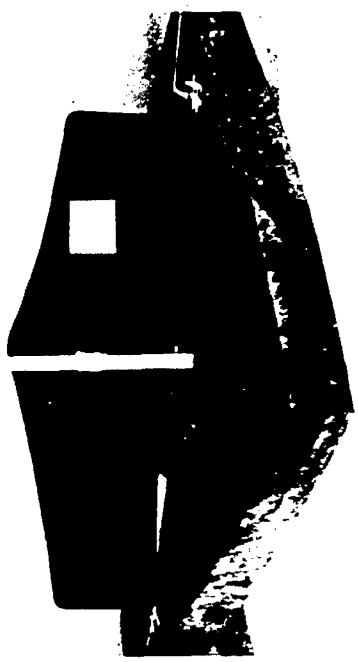


Bottom of Plate With Visible Cracks Indicated by Marker

Figure 5-18a. Weld Test Plate Condition Following Testing (Test Charge 6)



Bottom of Plate With Visible Cracks
Indicated by Marker



Top of Plate Showing Method of Measuring
Dent

Figure 5-18b. Weld Test Plate Condition Following Testing (Test Charge 7)

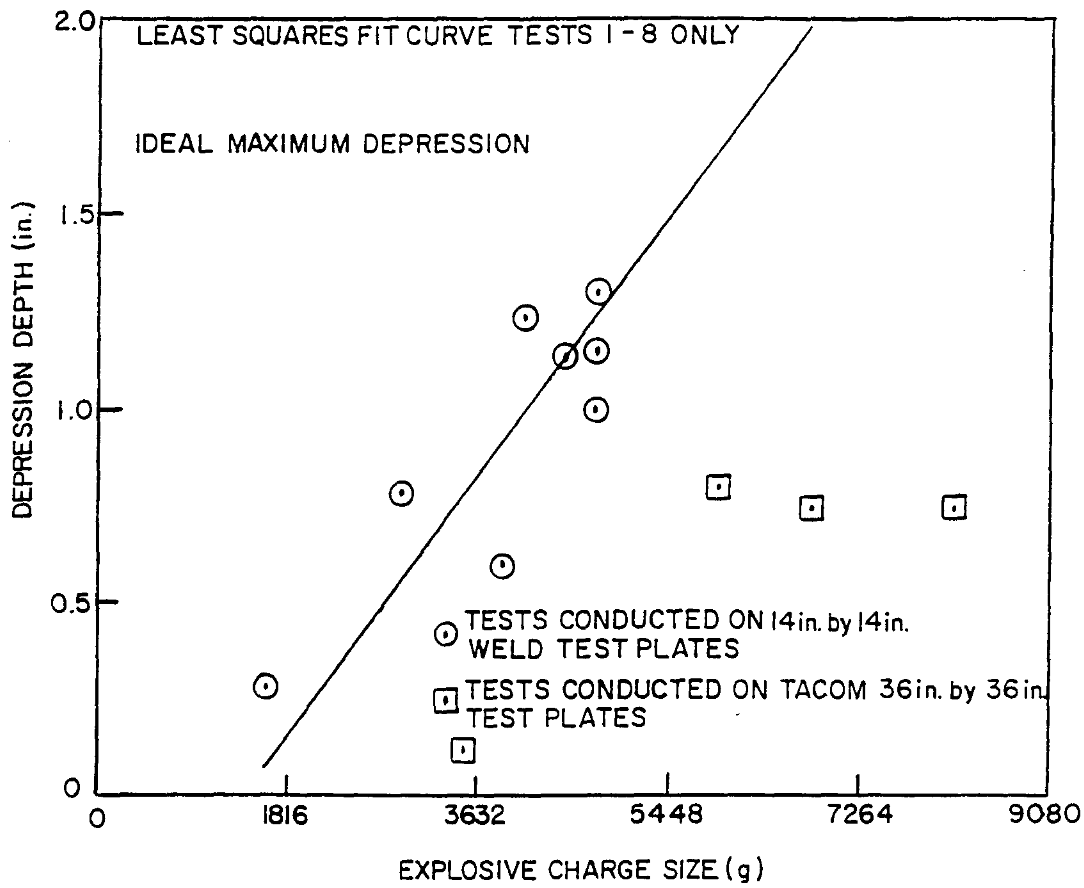


Figure 5-19. Explosive Charge Size vs. Depression Depth

No attempt was made to size a charge for the minimum depression (0.875 in.) because if the maximum depression could be formed, the minimum depression would be no problem. Therefore, 6-in.-D charge sizes were determined. Charges of 40% dynamite weighing 5,902 g (Test Charge 9) and 6,810 g (Test 11) were expected to bracket the required depressions.

5.8. Tests of Full-Sized Weld Test Plates for Comparison Tests (Task 6)

On 19 May 1987, the remaining four fabricated charges were tested. As in Task 4, these charges could not be tested in our Livingston facility. They were sent to Explosive Fabricators in Louisville, Colorado, along with the charges from Task 4 and the weld test plates supplied by TACOM. Explosive Fabricators again supplied all explosive (40% dynamite) caps, timbers, and steel bar blocking to support the test plates during testing.

Both TACOM weld test plates were set up as shown in Figures 5-12 and 5-13. Steel bars 2 in. by 4 in. were placed on 6- by 6-in. timbers. These timbers were placed along the four sides of the test plates and shimmed so that the bars contacted the plates in a manner similar to the 14- by 14-in. test plates. Charges were then placed on the welds, as shown in Figure 5-20. (The figure also shows the two impressions from the TACOM tests.) Standoff distance was 1 in. from the top of the weld to the projectile tip. A paperboard cylinder was placed over the charge and filled with approximately 2.5 ft^3 of sand (16 in. in D by 24 in. high). The charge was detonated and the resultant impression and crack length were measured.

Test Charge 9 was 5,902 g of 40% dynamite; dent depth was 0.8 in.; 16 in. of weld crack was noted on the face and 24 in. on the back. Test Charge 11 was 6,810 g of 40% dynamite; dent depth was 0.75 in.; no cracks were noted. A maximum load of 5,448 g of 40% dynamite was used in the one remaining 5-in. charge (Test Charge 10). The depression depth measured for Test Charge 10 was 0.12 in.; no cracks were noted. As these dents were much smaller than required, the remaining 6-in. charge (Test Charge 12) was increased to 8,172 g and detonated on the TACOM projectile test plate. The measured depression depth was 0.75 in., and a 5.88-in. crack was noted on the back. In addition, the original crack generated during the projectile test continued to fracture for the remaining length of the plate, and one section separated from the plate. All cracks were observed visually.

Evaluation of the center pieces of the projectiles from Test Charges 9, 11, and 12 indicates that charges of this configuration are limited to explosive loads of approximately 4,767 g of 40% dynamite or less.

Loads in excess of this are not modulated sufficiently by the wax buffer to protect the projectile from the shock wave. Thus the projectile is destroyed before it forms the depression in the test plate. Figure 5-21 shows the three projectiles and the typical tensile fractures caused by

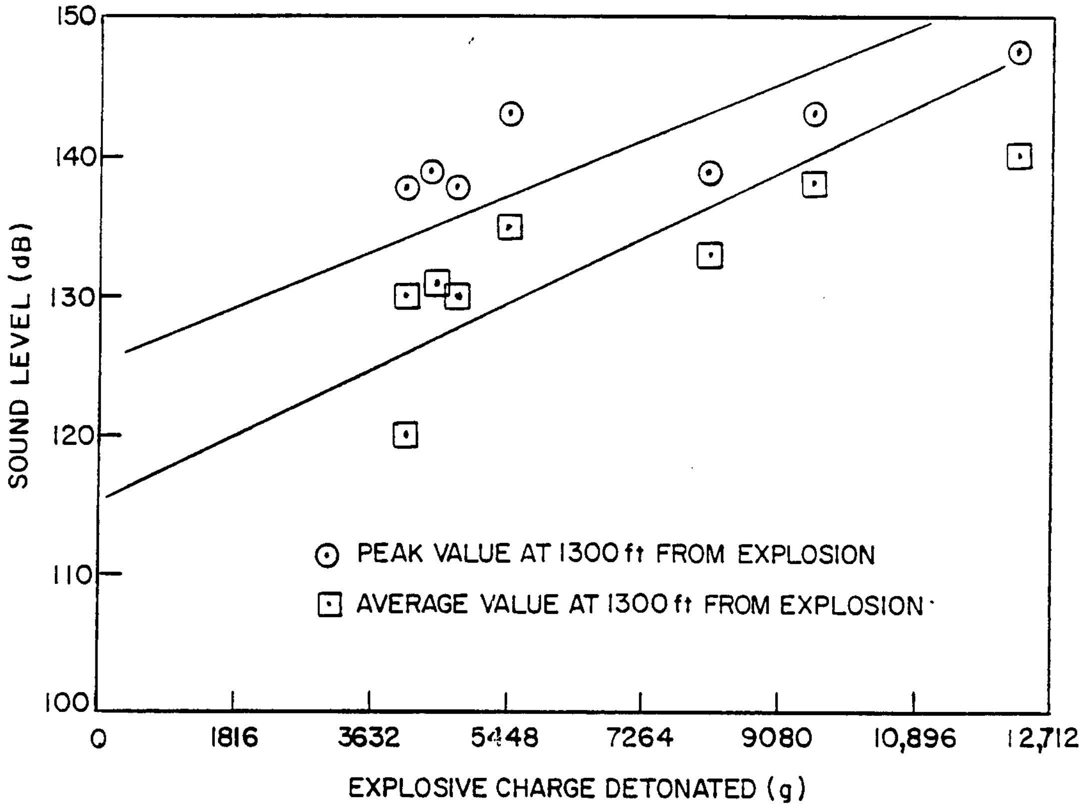


Figure 5-20. Test Locations on TACOM Test Plates

5-in. Test Charges 2, 10, and 4

6-in. Test Charges 9, 11, and 12

Figure 5-21. Projectile Condition After Detonation of Charge the reflected detonation-wave tensile stresses formed at the interference points. A plate weld imprint on the projectile end indicates that the projectile contacted the plate and projectile fracture occurred at approximately the same time.

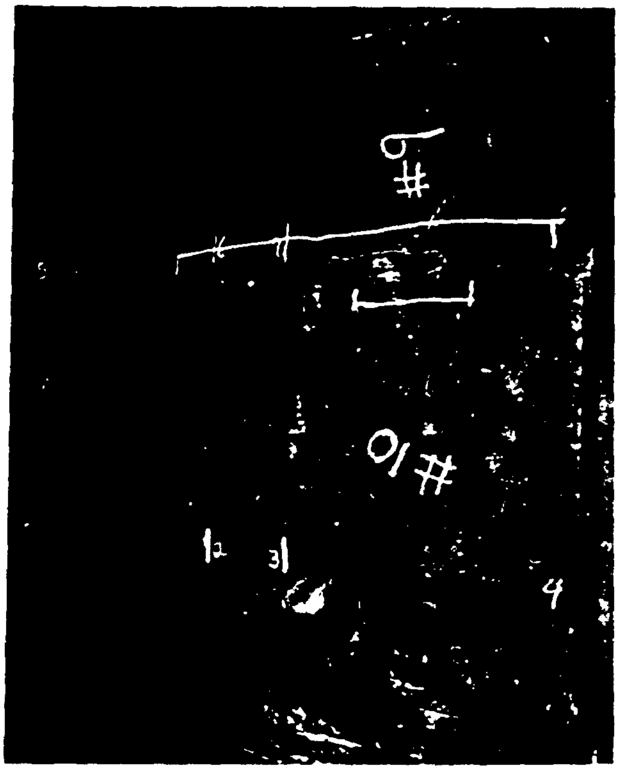
These results suggest that additional buffer material is required to modulate the shock wave or that a larger diameter projectile should be used. Such a projectile would require less explosive per square inch of projectile; the shock wave would thus be reduced to an acceptable level.

Figure 5-22 shows the TACOM test plate (marked "scrap") on which Test Charges 9 (6 in.) and 10 (5 in.) were detonated. Test Charges 11 and 12 (6 in.) were detonated on the TACOM projectile test plate (Figure 5-23).

Table 5-3 presents charge data and results.

5.9. Sound Test Level

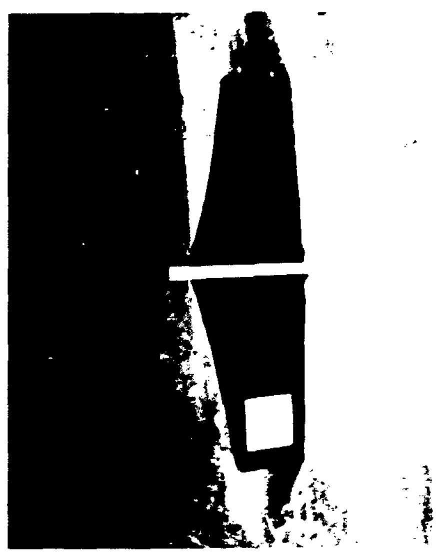
Sound measurements were conducted on all but two tests (Test Charges 4 and 9). These two were eliminated because other work was being conducted simultaneously. Tests Charges 7 and 8 were fired together, as were Test Charges 10 and 11. In each firing, the two individual test charge explosive weights were added together for evaluation. Sound measurements were made using a General Radio Model 1551C S/N3224 Sound Level Meter with an impact noise analyzer, Model 1556B S/N1920. Measurements were taken 1,300 ft away from the detonated charge--the nearest safe area used by Explosive Fabricators. Test sound levels at this point were within 10% of the meter limit. Sound meter settings were: 20 kilocycles frequency response, fast response, -140 dB (which allows measurement from 120 to 150 dB), 0.01-second measurement time, and measurement of positive pulse. Sound measurements indicated sound levels of 120 to 140 dB average value and 130 to 147.5 dB for peak value. At that distance, weather conditions (e.g., wind, humidity and clouds) have a significant effect on the sound levels measured. Table 5-2 lists measured values, and Figure 5-24 plots charge size vs. sound level. No ground vibration measurements were made.



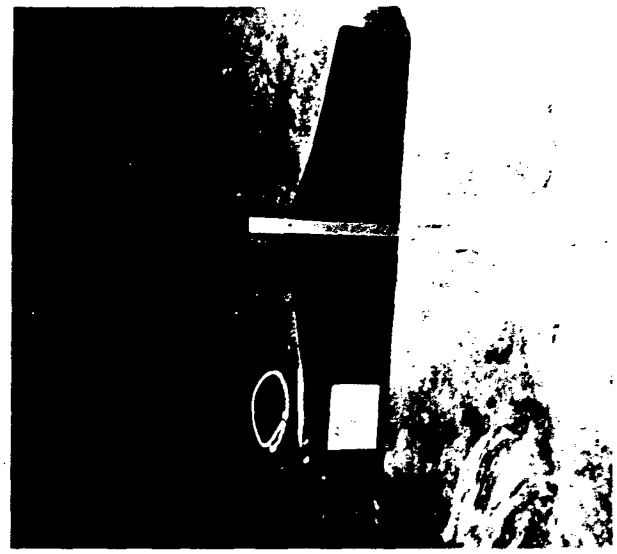
Bottom of Plate Showing Crack Locations for Test Charge 9 and No Crack Indications for Test 10

Overall Top View of TACOM Weld Test Plate Showing Test Charges 9 and 10 Impact Locations

Figure 5-22a. Top and Bottom Views of TACOM Weld Test Plate Marked "Scrap" Showing Test Impressions for Charges 9 and 10



Impact Test Position With Impression Measurement Being Taken (Charge 9 Location)



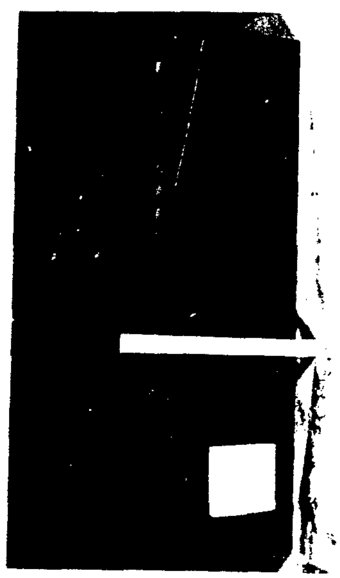
Impact Test Position With Impression Measurement Being Taken (Charge 10 Location)

Figure 5-22b. Top Views of TACOM Weld Test Plate With Ballistic Impressions and Test Charges 9 and 10

Overall Top View of TACOM Weld Test Plate Containing Two Ballistic Impacts and Test Charges 11 and 12 Impact Locations

Bottom of Plate Showing Crack Locations for Test Charge 12 Only (Original Crack From Ballistic Impact Continued Through Plate)

Figure 5-23a. Top and Bottom Views of TACOM Weld Test Plate Marked "Scrap" Showing Test Impressions for Charges 11 and 12



Impact Test Position With Impression Measurement Being Taken (Charge 11 Location)

Impact Test Position With Impression Measurement Being Taken (Charge 12 Location)

Figure 5-23b. Top Views of TACOM Weld Test Plate with Ballistic Impressions and Test Charges 11 and 12

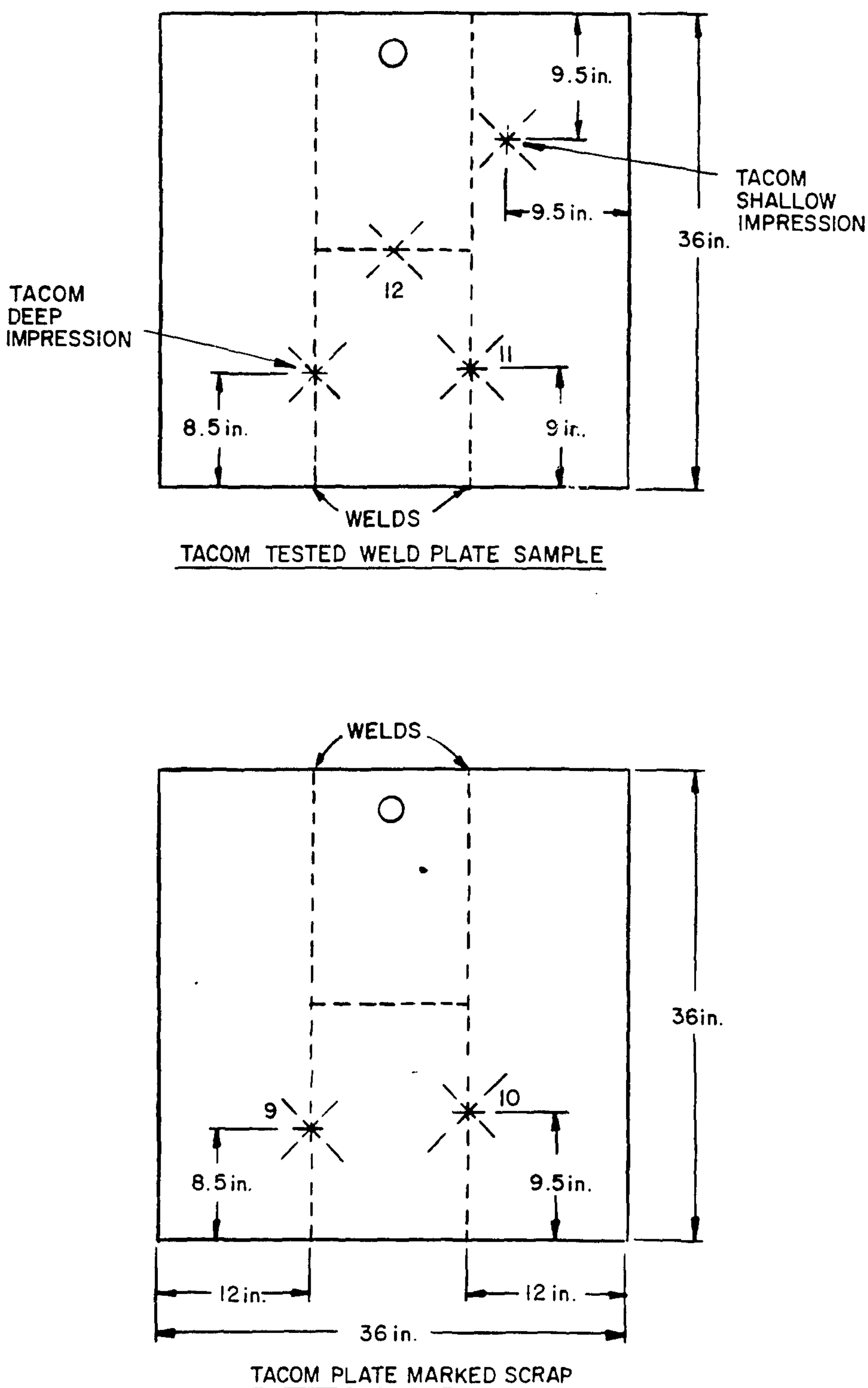


Figure 5-24. Relationship Between Size of Explosive Charge and Sound Level

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