Report 1839

STEEL CUTTING WITH HIGH-EXPLOSIVE CHARGES

by

James A. Dennis

December 1965

U. S. ARMY ENGINEER RESEARCH AND DEVELOPMENT LABORATORIES
FORT BELVOIR, VIRGINIA

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U. S. ARMY ENGINEER RESEARCH AND DEVELOPMENT LABORATORIES
FORT BELVOIR, VIRGINIA

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STEEL CUTTING WITH HIGH-EXPLOSIVE CHARGES

Task 1M624101D46501

December 1965

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The Commanding Officer
U. S. Army Engineer Research and Development Laboratories

Prepared by

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Combat Engineering Division
Military Department

FOREWORD

The investigation covered in this report was conducted under the authority of Task 1M624101D46501, "Engineering Studies and Investigations, Demolitions." A copy of the Research and Technology Resume is included as Appendix A.

Tests covered herein were performed at the Barrier Experimental Facility, Fort Belvoir, Virginia, and at Camp A. P. Hill, Virginia, during May 1962 through May 1965.

The investigation was under the direction of James A. Dennis, Combat Engineering Division, Military Department. Arthur T. Stanley, Physicist, formerly of the Computation and Analysis Division, Technical Service Department, assisted with the tests in 1962. Richard E. Deighton, Mathematician, also formerly of the Computation and Analysis Division, made the statistical analyses of the data obtained from the factorial experiments. The demolition testmen were Arthur L. Limerick and Bert Sheets of the Combat Engineering Division, Military Department. The photographers were Ralph E. Fravel and Harold E. Mohaupt of the Pictorial Sciences Division, Technical Service Department. The experimental program was under the general supervision of B. F. Rinehart, Chief, Obstacles, Demolitions, and Emplacements Branch, Combat Engineering Division, Military Department.

SUMMARY

This report covers an experimental program in which new techniques for explosive demolition of structural steel shapes were developed and evaluated in connection with the examination of current U. S. Army methods of steel cutting with high-explosive charges. The steel-cutting effectiveness of Composition C-4, paste, and EL506A-5 Detasheet explosives was determined by demolition tests in which steel angles, bars, beams, cables, channels. plates, and pipes were cut with contact charges and linear shaped charges. Diamond-shaped charges severed round and square steel bars through the cutting effect of explosively induced stress waves. A simplified steel-cutting formula that not only computes the explosive charge but also specifies its configuration, dimensions, and positioning on the target was devised, investigated, and compared with the U. S. Army steel-cutting formula, which only determines the explosive weight of the charge.

The report concludes that:

a. Both charge width and charge thickness have significant effects on the steel-cutting efficiency of contact explosive charges.

b. The point of charge initiation does not significantly affect the shattering power of contact explosive charges on steel.

c. A 3:1 ratio of charge width to charge thickness is optimum for contact explosive charges calculated to cut structural steel in thicknesses of 3 inches or less.

d. The formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ is more accurate and efficient than the U. S. Army formula $P = \frac{3/8\ A}{1.34}$ for calculation of contact charges of Composition C-4, paste, and EL506A-5 Detasheet explosives to cut structural steel.

e. Composition C-4, paste, and EL506A-5 Detasheet explosives are equally effective as contact charges for cutting structural steel; because of its variable density, paste explosive is less effective than Composition C-4 explosive for cutting round steel bars.

f. The optimum offsets between linear contact charges emplaced to cut from both sides, for reliable explosive demolition of steel beams, are the alignment of the edge of one charge opposite the center of the charge on

the other side of beams with steel thicknesses of less than 2 inches, and the alignment of the edge of one charge opposite the edge of the charge on the other side of beams with steel thicknesses of 2 inches or more.

g. The detonating cord firing system is more reliable than electric blasting caps in series circuits for simultaneous detonation of multiple contact charges used in the explosive demolition of steel beams.

h. The diamond charge technique is more effective and dependable than either the cross-fracture or dual-offset charge technique for explosive cutting of steel bars.

CONTENTS

Section	Title		Page
	FOREWORD		ii
	SUMMARY		iii
	ILLUSTRATIONS		vi
	TABLES		xi
I	INTRODUCTION		
	1.	Subject	1
	2.	Background and Previous Investigation	1
	3.	Mechanism of Steel Cutting with Explosives	6
	4.	Significance of Explosive Charge Dimensions	11
II	INVESTIGATION		
	5.	Characteristics of Test Explosives	15
	6.	Statistical Experiments	18
	7.	Explosive-Cutting Tests on Steel Plates	29
	8.	Explosive-Cutting Tests on Structural Steel Shapes	35
	9.	Explosive-Cutting Tests on Wire Rope	60
	10.	Explosive-Cutting Tests on Steel Bars	64
	11.	Steel-Cutting Experiments with Diamond Charge Technique	77
	12.	Explosive-Cutting Tests on Steel Pipe	87
	13.	Description of Linear Shaped Charges	87
	14.	Steel-Cutting Experiments with Linear Shaped Charges	94
III	DISCUSSION		
	15.	Evaluation of Test Results	99
IV	CONCLUSIONS		
	16.	Conclusions	124
	LITERATURE CITED		125
	APPENDICES		
	A.	Authority	128
	B.	Statistical Analyses of Steel-Cutting Experiments	129
	C.	Summary of Test Data	135

ILLUSTRATIONS

Figure	Title	Page
1	U. S. Army-Recommended Charge Placement Methods	4
2	Destructive Effects from Explosive Charge Detonated in Contact with 1-Inch Steel Plate	8
3	Destructive Effect from 4-Inch-Square Explosive Charge Detonated at Its Center in Contact with Steel Plate	10
4	Cross-Fracture Splits and Longitudinal Split Formed in Steel from Center-Point Detonation of 1/2- by 2- by 11-Inch Contact Explosive Charge	11
5	U. S. Army Demolition Blocks of High Explosives	13
6	Explosive Blocks Emplaced on Steel Beam; TNT and C-4	14
7	Paste Explosive in 100-Pound Container	16
8	EL506A-5 Detasheet Flexible Explosive	18
9	Six-Inch-Long Explosive Charges of Variable Widths and Thicknesses Used in Factorial Experiments	19
10	Use of Wooden Mold to Fix Dimensions of Paste and Aluminized Paste Explosive Charges	20
11	Measurements of Charge Yields for Factorial Experiments	21
12	Effects of Variations of Charge Widths on Shattering Power of Paste Explosive Charges	24
13	Effects of Variations of Charge Widths on Shattering Power of C-4 Explosive Charges	25
14	Rectangular Explosive Charges Emplaced to Cut 1- by 12- by 18-Inch Steel Plates	31
15	One-Inch Mild Steel Plate Not Cut by 1/2 Pound of Paste Explosive in 3/4- by 1- by 12-Inch Charge and 2/3 Pound of Paste Explosive in 1/2- by 2- by 12-Inch Charge	33

ILLUSTRATIONS (cont'd)

Figure	Title	Page
16	One-Inch Mild Steel Plate Severed by 1-1/3-Pound of C-4 Explosive Charge of 1 by 2 by 12 Inches	34
17	Steel Plate Uncut at Center under Point of Cap Initiation of 1/4-Inch-Thick Explosive Charge	35
18	Experimental Explosive Charges on Steel Angles	38
19	Cutting Effect of Contact Explosive Charge on Steel Angle	39
20	Wide-Flange Steel Beams Used for Explosive-Cutting Tests; 36WF300 and 14WF426	41
21	Charge Placement and Priming Technique Recommended by SRI for Explosive Cutting of Steel Beams	44
22	Detonating Cord Firing System Used for Priming and Simultaneous Explosion of Continuous and Half-Flange Charges on Steel Beams	45
23	U. S. Army Charge Placement Method Evaluated for Cutting Steel Beams with Explosive Charges Detonated at Center	47
24	Priming of Continuous Explosive Charges for Simultaneous Detonation by Detonating Cord Priming Assembly and by Electric Blasting Caps	48
25	Hand Placement of Paste Explosive on to Grease-Coated Steel Beam	50
26	Experimental Charges of Composition C-4 and Paste Explosives Held on 24WF76 Steel Beams by Grease	51
27	EL506A-5 Detasheet Explosive Charge Emplaced on Grease-Coated Surface of 24WF76 Steel Beam	52
28	Typical Incomplete Explosive Cuts on Wide-Flange Steel Beams	53
29	Wide-Flange Steel Beams Severed by Contact Explosive Charges	55

ILLUSTRATIONS (cont'd)

Figure	Title	Page
30	Longitudinal Splits Formed on Steel Beams by Contact Explosive Charges	56
31	Criticality of Offset between Explosive Charges Placed to Cut Wide-Flange Beams from Both Sides	57
32	Excessive Destructive Effect Produced on Wide-Flange Steel Beams by Explosive Charges with Thicknesses and Widths Exceeding the Optimum	58
33	Spall Damage without Tensile Fracture Inflicted on Web of Steel Beam by Excessively Thin Explosive Charge	59
34	Contact Charges of Comparison C-4 and EL506A-5 Detasheet Explosives Emplaced on 15 by 3-3/8 Steel Channels	61
35	Typical Explosive Cuts on 15 by 3-3/8 Steel Channels	62
36	Dual Charges of Paste Explosive Primed for Simultaneous Detonation to Shear Wire Rope, 1-1/2 Inches in Diameter	63
37	Improved Plow-Steel Wire Rope, 1-1/2 Inches in Diameter, Severed by Dual-Explosive Charges Detonated Simultaneously	64
38	Explosive Charges Prefabricated for Cutting Round Steel Bars	66
39	Cross-Fracture Explosive Technique for Cutting Steel Bars	68
40	Test Setup and Results for Dual-Explosive Charges Detonated to Cut Square Steel Bars from Opposite Sides	70
41	End-Primed 2-1/4-Pound Paste Explosive Charge Used to Cut 4-Inch-Square Steel Bar by Major Cross Fracture	71
42	Incomplete Cross Fracture Produced in 4-Inch-Square Steel Bar by End-Detonated Paste Explosive Charge of Insufficient Length and Thickness	72

Figure	Title	Page
43	Center-Primed C-4 Explosive Charge Used to Break 2-Inch-Square Steel Bar by Two Cross Fractures	73
44	Paste and C-4 Explosive Charges Emplaced to Cut Round Steel Bars by Cross-Fracture Technique	75
45	Round Steel Bars Severed by Cross Fracture Produced by Explosion of Contact Explosive Charges	76
46	Saddle Charge Explosive Technique for Cutting Steel Bars	78
47	Saddle-Charge Setup and Test Results on Mild Steel Bar, 4 Inches in Diameter	79
48	Diamond Charge Explosive Technique for Cutting Both Round and Square Steel Bars	80
49	Cutting of Round Steel Bar, 6 Inches in Diameter, by Tensile Fracture Induced by Diamond-Shaped Charge of EL506A-5 Detasheet Explosive	82
50	Four-Inch-Square Steel Bar Cut by Tensile Fracture Induced by Diamond-Shaped Charge of Detasheet Explosive	83
51	Incomplete Tensile Fractures Formed in Round and Square Steel Bars by Means of Diamond-Shaped Charges of Insufficient Dimensions and Explosive Weight	84
52	Complete Tensile Fracture Produced in Steel Bar, 6 Inches in Diameter, by Means of Diamond-Shaped Charge	85
53	Test Setup and Results for Demolition of Thick-Walled Steel Pipe with Paste Explosive Charge Encircling Circumference	88
54	Paste Explosive Charge Severed Thick-Walled Steel Pipe by Cross Fracture	89
55	West German Army Linear Shaped Charge, DM 19	91

ILLUSTRATIONS (cont'd)

Figure	Title	Page
56	USAERDL-Fabricated Linear Shaped Charge	92
57	Small Linear Shaped Charges Fabricated from Mark 7 Demolition Charge Containers and Commercial Magnets	93
58	Typical Test Setup and Results of DM 19 Linear Shaped Charge Firings on Steel Plates	95
59	Typical Test Setup and Results of USAERDL Linear Shaped Charge Firings on Steel Plates	96
60	Emplacement of Small Linear Shaped Charges for Cutting 10WF49 Steel Beams	97
61	Typical Cuts Made on 10WF49 Steel Beam by Jets from Small Linear Shaped Charges	98
62	One-Inch-Thick Mild Steel Plate of 18 Linear Inches with Free Reflection Surface Severed by 0.78-Pound C-4 Explosive Charge	108
63	Explosive Weights Calculated to Cut 18 Linear Inches of Steel by Various Formulas	111
64	Charge Placement for Explosive Cutting of Wide-Flange Beams with Steel Thicknesses of Less Than 2 Inches	114
65	Charge Placement for Explosive Cutting of Wide-Flange Beams with Steel Thicknesses of 2 Inches or More	115

TABLES

Table	Title	Page
I	Comparative Effects of Explosives	3
II	Test Data for Factorial Experiment 1	23
III	Test Data for Factorial Experiment 2	26
IV	Test Data for Factorial Experiment 3	28
V	Test Data for Factorial Experiment 4	29
VI	Details of Steel Test Beams and Experimental Explosive Charges	42
VII	Summary of Test Results with Diamond-Shaped Charges	86
VIII	Comparative Effects of the Three Test Explosives	102
IX	Comparison of Experimental Data Taken from Explosive-Cutting Tests on Structural Steel	105
X	Significance of Priming Methods in Explosive Demolition of Steel Beams	118
XI	Comparative Effects of Explosive Techniques Used to Cut Steel Bars	121
XII	Analysis of Variance for Experiment 1 for Explosive Test Results on Steel Plates	130-131
XIII	Tukey's Method of Simultaneous Confidence Intervals for Experiment 2	132
XIV	Analysis of Variance for Experiment 3	133
XV	Analysis of Variance for Experiment 4	134
XVI	Summary of Explosive-Cutting Test Results on Steel Plates	136-140
XVII	Summary of Explosive-Cutting Test Results on Structural Steel Angles	141
XVIII	Summary of Explosive-Cutting Test Results on Steel Beams and Channels	143-148

TABLES (cont'd)

Table	Title	Page
XIX	Summary of Explosive-Cutting Test Results on Wire Ropes	149-150
XX	Summary of Explosive-Cutting Test Results on Square Steel Bars	151
XXI	Summary of Explosive-Cutting Test Results on Round Steel Bars	152-153
XXII	Summary of Steel-Cutting Test Results Obtained with Saddle Charges	154
XXIII	Summary of Steel-Cutting Test Results Obtained with Diamond-Shaped Charges	155-156
XXIV	Summary of Explosive-Cutting Test Results on Steel Pipe	157
XXV	Summary of Linear Shaped Charge Test Results on Steel Plates	158

STEEL CUTTING WITH HIGH-EXPLOSIVE CHARGES

I. INTRODUCTION

1. Subject. The continued military employment of chemical explosives for demolition of numerous steel targets imposes a requirement for development of improved techniques for steel cutting with high explosives. Because bridge demolitions and the destruction of obstacles and equipment usually involve some applications of explosives for steel cutting and many U. S. Army explosive steel-cutting methods are of pre-World War II origin, examination of military techniques for explosive demolition of steel was considered desirable. Accordingly, this report covers an experimental program in which not only current U. S. Army methods of steel cutting with explosives were investigated, but also new techniques for explosive demolition of structural steel shapes were devised and evaluated. During the investigation, Composition C-4, paste, aluminized paste, and EL506-A Detasheet explosives were evaluated in demolition experiments in which steel angles, bars, beams, cables, channels, plates, and pipes were severed by cutting with contact charges, linear shaped charges, and explosively induced stress waves. In an experiment on steel plates, statistical procedures were used to establish the significance of various types of explosives, thicknesses of charges, widths of charges, and points of charge initiation on the steel-cutting effects of contact explosive charges.

2. Background and Previous Investigation. Prior to 1945, to compute the explosive charges required to cut I-beams, built-up girders, steel plates, columns, and similar structural steel sections, the United States Army used the empirical formula N = 3/4 A, in which N was the required number of 1/2-pound TNT blocks and A was the cross-sectional area of the steel member in square inches. The formula N = 2 A, with N and A having the same meanings, as just stated, was used to calculate the explosive charges necessary for cutting steel-reinforcing bars, cables, chains, and other round members of such small size that good contact between the steel and explosive was practically impossible. Explosive charges calculated by those formulas were placed along one side of the steel member at the desired line of rupture with the largest portion of the charge concentrated against the greatest cross section of the steel member. If the explosive charge was large or the form of the steel member was such that the charge had to be distributed on opposite sides, the opposing portions of the charge were offset and detonated simultaneously to produce a shearing effect (1).

In the May 1945 edition of Field Manual FM 5-25, Explosives and Demolitions, the U. S. Army changed the steel-cutting formula to $P = 3/8\ A$ for structural steel and $P = A$ for rods, bars, and cables of small diameters (D) where P was the pounds of TNT required to cut the steel member and A was the cross-sectional area of the member in square inches. The change in the formula to express the calculated charge in pounds of TNT instead of the number of 1/2-pound blocks of TNT was accomplished by reducing the constants in the formulas to one-half the original figure; that is, $N = 3/4\ A$ became $P = 3/8\ A$ and $N = 2\ A$ became $P = A$. The Army still uses the $P = 3/8\ A$ formula for calculating explosive charges to cut structural steel targets and round members with diameters of more than 2 inches, but to cut cables, rods, and chains with diameters of 2 inches or less, alloy and high-carbon steel, the formula $P = D^2$ is used (pounds of TNT equals the diameter squared).

Because explosive charges calculated by the Army steel-cutting formulas are given in required pounds of TNT, when an explosive of greater or lesser effectiveness than TNT is used, the calculated charge weight is adjusted by the TNT equivalent or relative effectiveness of that explosive in relation to TNT. For example, some comparative effects of several different explosives, both commercial and military, are presented in Table I. The relative effectiveness of each explosive is listed in the second column to the table, while the TNT equivalent which, as has been stated, is the reciprocal of the relative effectiveness, is given in the third column. The values of both columns are based on TNT taken as unity (1.00). Hence, if the calculated charge for a specific steel member came to 10 pounds of TNT, the same cutting effect could be obtained with 7.5 pounds of Composition C-4 explosive or 8.4 pounds of Tetrytol (2)(3)(4)(5).

For demolition of steel members, the U. S. Army still recommends the use of single charges placed on one side to cut thin steel targets of simple shape, with the largest portion of the charge nearest the greatest cross section of the member. Two charges, distributed on opposite sides of the member and offset to produce a shearing action as the charges detonate simultaneously, are specified to cut wide-flange beams, shafts with large diameters, and other irregularly shaped targets that cannot be cut by a single charge distributed on one side. On built-up members such as box girders where irregular shape or rivets make close contact between the explosive and the steel difficult to obtain, the charge is increased. Composition C-4 explosive is considered best for use on irregular steel shapes, and if TNT must be used for steel cutting, present U. S. Army charge placement methods prescribe the removal of the TNT blocks from their containers,

Table I. Comparative Effects of Explosives

Explosive	Relative Effectiveness	TNT Equivalent	Loading Density (g/cc)	Detonation Velocity (fps)
TNT	1.00	1.00	1.57	21,000
Tetrytol	1.20	0.84	1.60	23,000
Tetryl	1.26	0.80	1.55	23,400
Composition C-2	1.34	0.75	1.57	26,000
Composition C-3	1.34	0.75	1.59	26,000
Composition C-4	1.34	0.75	1.59	26,000
Ammonium Nitrate	0.42	2.38	1.00	11,218
Nitrostarch	0.86	1.16	1.75	15,000
RDX (Cyclonite)	1.50	0.67	1.65	26,830
Composition B	1.35	0.74	1.65	25,500
Military Dynamite	0.92	1.09	1.10	20,000
Gelatin Dynamite 60 percent	0.76	1.32	1.34	16,000
Straight Dynamite 60 percent	0.83	1.21	1.22	19,000

as shown in Fig. 1 (3). This procedure is considered to be impractical for combat demolition missions.

The U. S. Army Engineer Research and Development Laboratories (USAERDL) in 1948, however, performed comparative steel-cutting tests between cylindrical linear shaped charges loaded with Composition C-3 explosive and similar charges loaded with German Composition X explosive (6). To evaluate the two explosives, linear shaped charges containing those explosives were detonated from steel plates at varying standoff distances; the depths of penetrations that the charges made in the plates determined their effectiveness. In the report of these experiments, it was concluded that Composition C-3 explosive was equal to German Composition X explosive in effectiveness as the explosive filler for linear shaped charges, that cylindrical linear shaped charges had potential application for cutting steel structures, and that linear shaped charges will cut homogenous steel sections of a thickness equal to about 80 percent of the diameter of the charge.

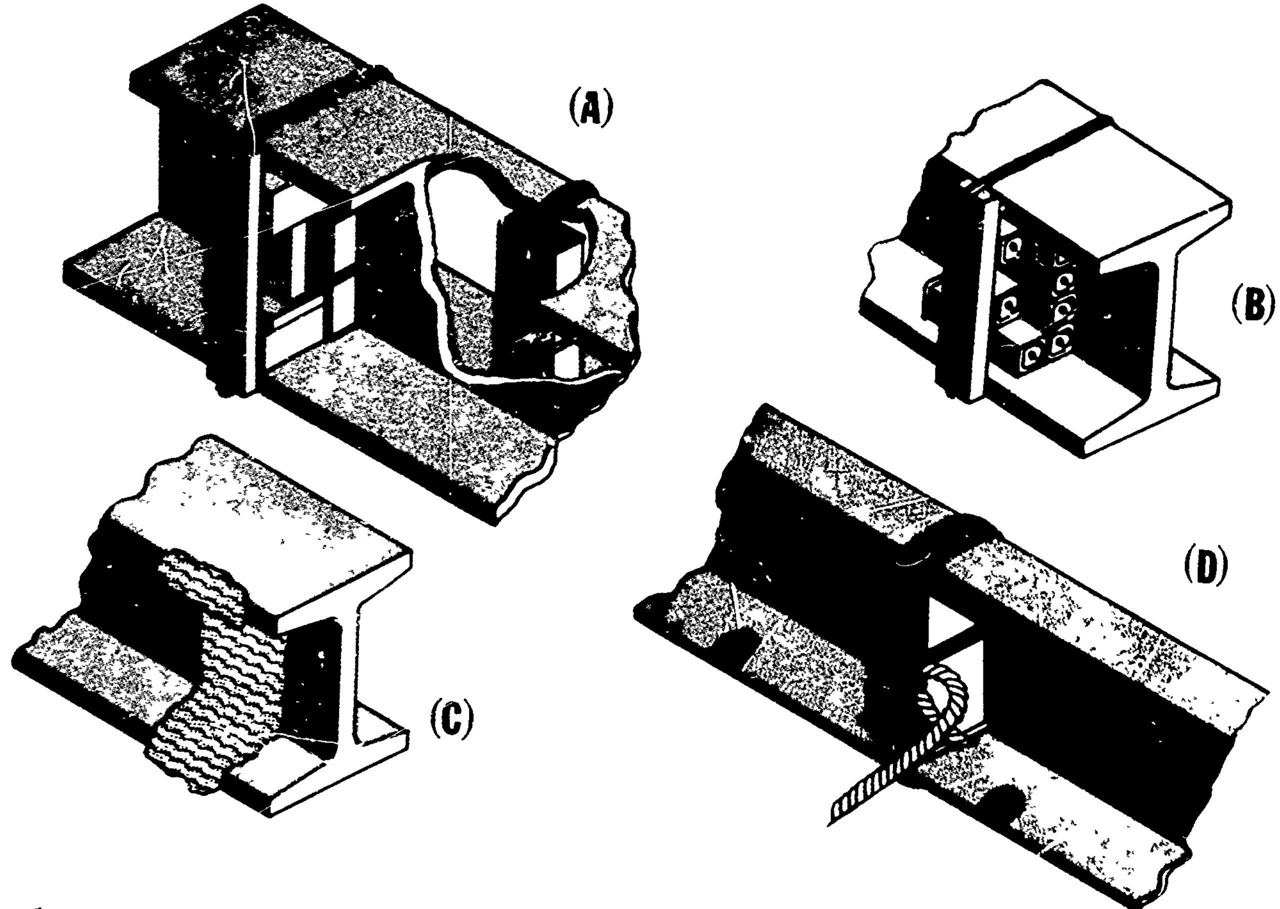


Fig. 1. U. S. Army-recommended charge placement methods used for cutting structural steel. (a) On two sides; (b) on one side; (c) plastic explosives molded on I-beam; and (d) placement of charges to cut steel railroad rail.

USAERDL conducted extensive explosive steel-cutting experiments in 1953 and 1954. These tests established the superiority of Composition C-3 explosive over TNT for cutting steel shapes. The importance of using a minimum thickness of explosive and of placing the explosive in close contact with the steel was also demonstrated. Structural steel shapes, channels, American standard and wide-flange beams, and square bars were cut with only 28 to 65 percent of the Composition C-3 explosive calculated by the U. S. Army steel-cutting formula $P = \frac{3/8\,A}{1.34}$. Three pounds of Composition C-4 explosives cut a round steel bar, 8 inches in diameter, when the charge was formed in the shape of a diamond with the long axis wrapped around the steel bar, and detonated simultaneously at the two points of the short axis; for the round steel bar which was cut by tensile fracture from the collision of induced stress waves, the diamond-shaped charge used only 21 percent of the explosive required by conventional U. S. Army explosive-cutting techniques. These important explosive steel-cutting tests were not documented in a formal technical report, but they were the bases of improved steel-cutting methods that resulted from a USAERDL contract with a commercial research firm.

From June 1955 through May 1957, Poulter Laboratories of Stanford Research Institute (SRI), under contract with USAERDL, performed explosive experiments designed to develop improved techniques and formulas for demolitions with high explosives (7). During steel-cutting tests with blocks of TNT and strips of C-4 explosive detonated on steel plates, SRI personnel found that a certain minimum thickness and width of charge was required to split or cut a given thickness of steel under an explosive charge. Tests revealed that the 2-inch-square demolition block which contained 2-1/2 pounds of C-4 explosive was capable of consistently cutting a piece of steel no thicker than 1-1/2 inches; the 1-7/8-inch-square TNT blocks consistently cut pieces of steel, each of which was only 3/4 inch thick. But C-4 explosive charges which had rectangular cross sections 1 inch thick by 2 inches wide which weighed only 1-1/4 pounds always cut steel plates 1-1/2 inches thick; this effect demonstrated that about half of the 2-inch-square C-4 blocks of explosive was wasted when the charges were used intact to cut steel. As a result of their experimental program with steel-cutting explosive charges, which utilized and refined some of the explosive steel-cutting methods devised in the 1953-1954 USAERDL in-house demolitions research, SRI recommended that the Army demolition formulas for steel cutting be revised as follows:

To cut structural steel members and steel plates, use the formula $t = 1/2_T + 1/8$, where t is the charge thickness in inches and T is the thickness in inches of the steel to be cut; make the charge width four times as wide as the charge thickness, or 4t. With this formula, the explosive charge should be in close contact with the steel to be cut, and the length of the charge should be equal to the length of the desired cut.

To cut round steel bars up to 3 inches in diameter, the weight of the explosive in pounds (P) should equal 2/3 the diameter in inches or $P = 2/3\ D$. The explosive should be placed on only one side of the bar, the width of the charge should be slightly less than half the circumference (about 1/2 D), and the length of the charge should be at least three times the thickness of the bar (3D). The charge should be at least 1 inch thick and should be detonated from one end in order to produce a major cross fracture at the opposite end.

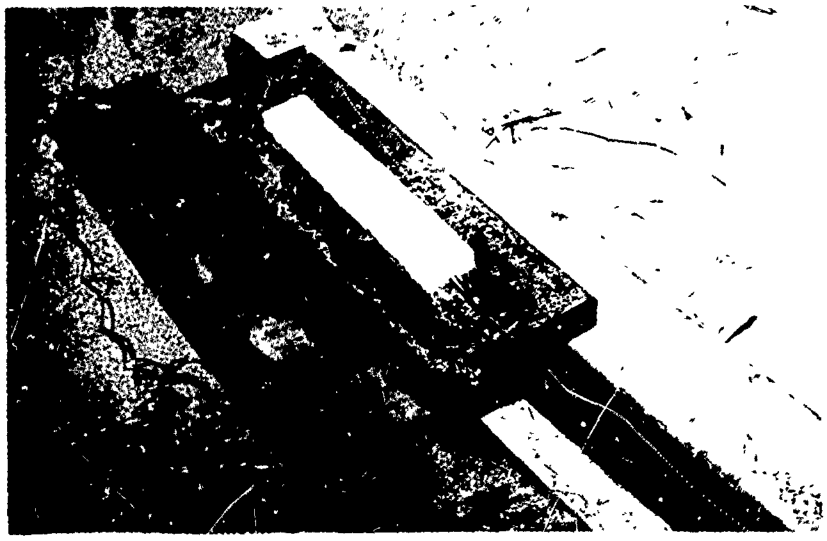
For cutting bars larger than 3 inches in diameter, the formula $P = 1/4\ D^2$ should be used (this formula is approximately the same as the present formula $P = 3/8\ A$ as stated in FM 5-25 except that the charge dimensions and placement are specified).

3. Mechanism of Steel Cutting with Explosives. A description of the mechanics of steel cutting with explosives requires, as an introduction, a discussion of the principles of detonation in high explosives. When a detonator explodes a charge of high explosive, a detonation zone in which the chemical reaction is taking place, travels through the explosive away from the point of initiation. This detonation zone is considered to include a narrow shock zone (10^{-5} cm) or shock wave in which little or no chemical reaction occurs but in which pressure reaches its peak. The detonation zone, therefore, includes both the shock zone and the chemical reaction zone (0.1 to 1.0 cm), and following the detonation zone are the detonation products (gas, heat, and pressure). The detonation products flow with great velocity but at a lesser rate than does the detonation zone (4).

Hence, when a high explosive detonates, the explosive changes violently from a solid into compressed gas at extremely high pressure; the rate of change is determined among other things by the type of explosive, the density, the confinement, and the dimensions of the charge. Detonation of high explosives, therefore, releases tremendous pressure in the form of a shock wave. This shock wave, which exists for only a few microseconds at any given point, may shatter and displace objects in its path as it proceeds from its point of origin. The shock wave from detonation of a high-explosive charge is transmitted direct to any substance with which the charge is in contact, other characteristics being equal; hence, the higher the velocity of detonation of an explosive charge, the greater is the shock transmitted.

A high-explosive charge detonated in direct contact with a steel plate produces four easily detectable destructive effects in the steel. An indentation or depression with an area about the size of the contact area of the explosive charge is made in the surface of the plate where the charge is exploded. A slab of metal, commonly called a spall or scab, is torn from the free surface of the plate directly opposite the explosive charge. This spalled metal approximates the shape of the explosive charge, but its area is usually greater than the contact area of the explosive. The steel is split or fractured under the exploded charge along its entire length, and finally, a cross fracture forms across the end of the charge away from the point of initiation (Fig. 2). Variations in the dimensions of the charge, the shape of the steel member under attack, the placement of the explosive charge in relation to the steel member, and the point of initiation of the charge can all alter the destructive effects described. Subsequent paragraphs describe and verify the effects of those variations.

William E. Drummond of SRI theorized that the cutting effect of high explosives on steel was caused by shock wave damage, not metal fatigue from pressure, and that this shock wave occurs when explosives have a detonation rate faster than the sonic velocity of the steel to be cut (8). The shock waves produce steel failure in two ways, by spalling the free surface of the plate, and by fracturing or splitting the plate at the boundaries of the explosive charge. The destruction of the steel takes place at two different times in two phases; and the spalling occurs first. As described by Drummond, the detonation which takes place in a high-explosive charge in direct contact with a steel plate transmits a compressive shock wave through the steel away from the detonating charge. Because this shock wave attentuates rapidly, its reactions with the nearest target interface opposite the detonation are of paramount significance. The compressive shock wave strikes the steel-air interface at the bottom of the plate, but because of the acoustic impedance at the interface, little of the shock wave can be transmitted from steel to air. Instead, it reflects from the surface as a rarefaction or tension wave. Because the shock wave is not just a moving point of compression, but an extended front that has a tail of gradually reduced strength, the effects of the reflected rarefaction wave are cancelled by the unreflected compressive tail. But as the compressive wave decreases in strength, the rarefaction or tension wave increases and soon results in a tension wave of strength that exceeds the tensile strength of the steel. At this point a spalling occurs and a new face is produced at the back of the steel plate. Some of the tail of the compressive wave is still traveling in the original medium, and this tail reflects from the new face as a renewed but weaker tension wave. The process continues until the remaining compressive wave is too weak when it is reflected to cause



(a) M5067

(b) M5068

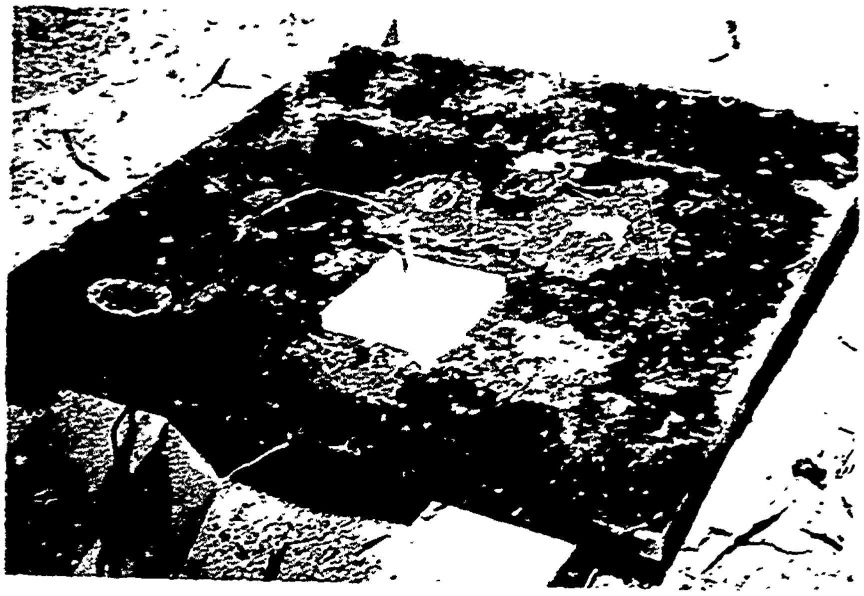
(c) M5069

Fig. 2. Destructive effects from (a) explosive charge detonated in contact with 1-inch steel plate ((b) and (c) cross fracture occurred at "y" opposite point of initiation at "x").

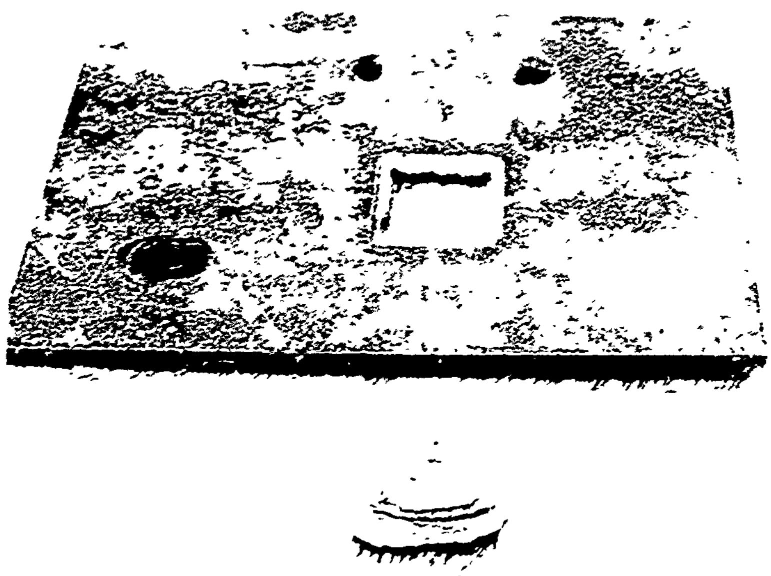
a spall. Normally, only one spall occurs with the amount of explosive used to cut steel, but multiple spalling does occur with overcharges (9).

Boundary splits, according to Drummond (8), are also caused by tension pulses or rarefaction waves formed within the steel at each side boundary. The original shock front is a compressive wave, and as such, compresses the steel through which it passes. However, the elastic limit of the steel is not exceeded, and after the passage of the shock wave, the compressed steel relaxes. This relaxation produces a rarefaction wave in the steel following the tail of the compressive shock wave. When the reflected tail of the shock wave and the relaxation wave meet, the combined strength of these waves exceeds the tensile strength of the steel and causes an internal crack. The continued juncture of these shock waves extends this crack, which finally breaks to the surface as boundary splits. If the charge is detonated at one end, two splits or cuts appear in the metal, a long cut down the middle of the charge and a cut across the end opposite the point of initiation (Fig. 2). But, if the charge is of sufficient width, two longitudinal cuts form rather than one cut down the center, and the end cut also forms. In addition, a charge detonated at the center will form splits at all four sides and will cut out a section of metal if the charge dimensions are great enough (Fig. 3).

Although the cutting effects of a high-explosive charge detonated on a steel plate occur within a few microseconds of the charge initiation, according to John S. Rinehart, a Research Physicist, they do take place in a certain order (10). Probably first the high pressure of the detonating charge severely compresses and forms a depression in the plate directly under the charge. This compression may be as much as 30 percent. Then, at the bottom of the plate, the compressive shock wave reflects as a tension wave and pulls a slab of metal from the back of the plate. Next, at the end of the charge away from the point of detonation, the reflected tension wave moves back toward the upper surface of the plate and meets a second rarefaction wave that is reflected within the steel at the charge boundary because of the greatly reduced pressure there. The meeting of these two tension waves within the plate tears the steel and forms a cross fracture or end cut. This cross fracture which actually begins in the interior of the plate, later is especially important in cutting steel bars, either square or round. Finally, along the length of the detonating charge other tension waves are formed within the steel at each side boundary. The meeting of these two forces within the steel pulls it apart and a long split down the center of the charge is formed; this longitudinal split actually begins to form at the bottom of the plate where the spall has just torn free. Longitudinal splits were utilized in subsequently described tests to cut structural



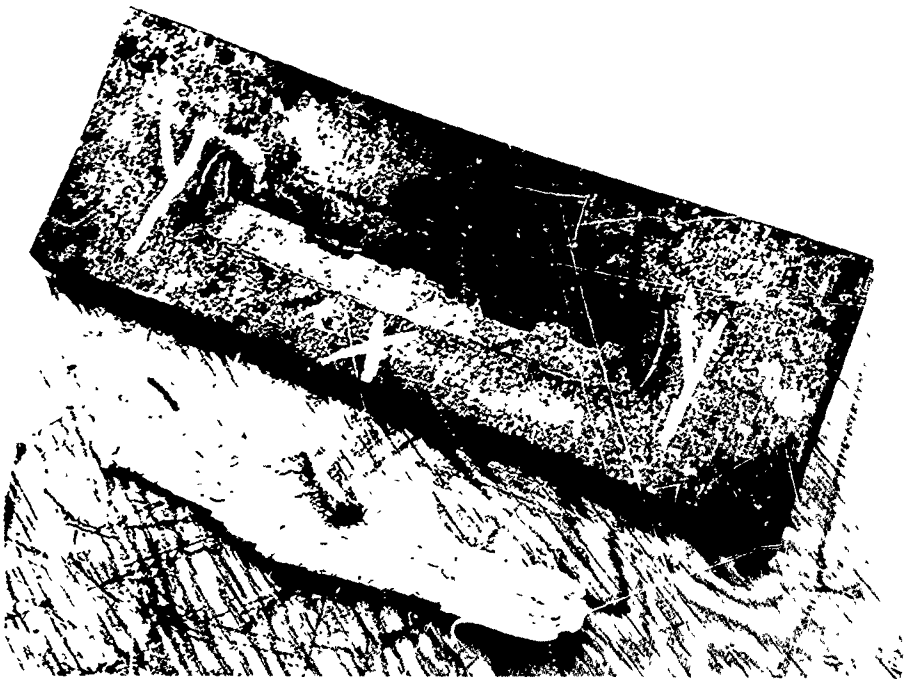
(a) M5074



(b) M5076

Fig. 3. Destructive effect from (a) 4-inch-square explosive charge detonated at its center in contact with steel plate ((b) "x" identifies point of charge initiation).

members like wide-flange beams, and steel plates. The spall apparently began to form slightly before the plate started to split along the length of the charge because the spall was not split. The cross fracture probably was formed before the longitudinal split was completed as the steel was not fractured beyond the end of the charge; the cross fracture completely stopped further progress of the longitudinal split (Fig. 4).



M5071

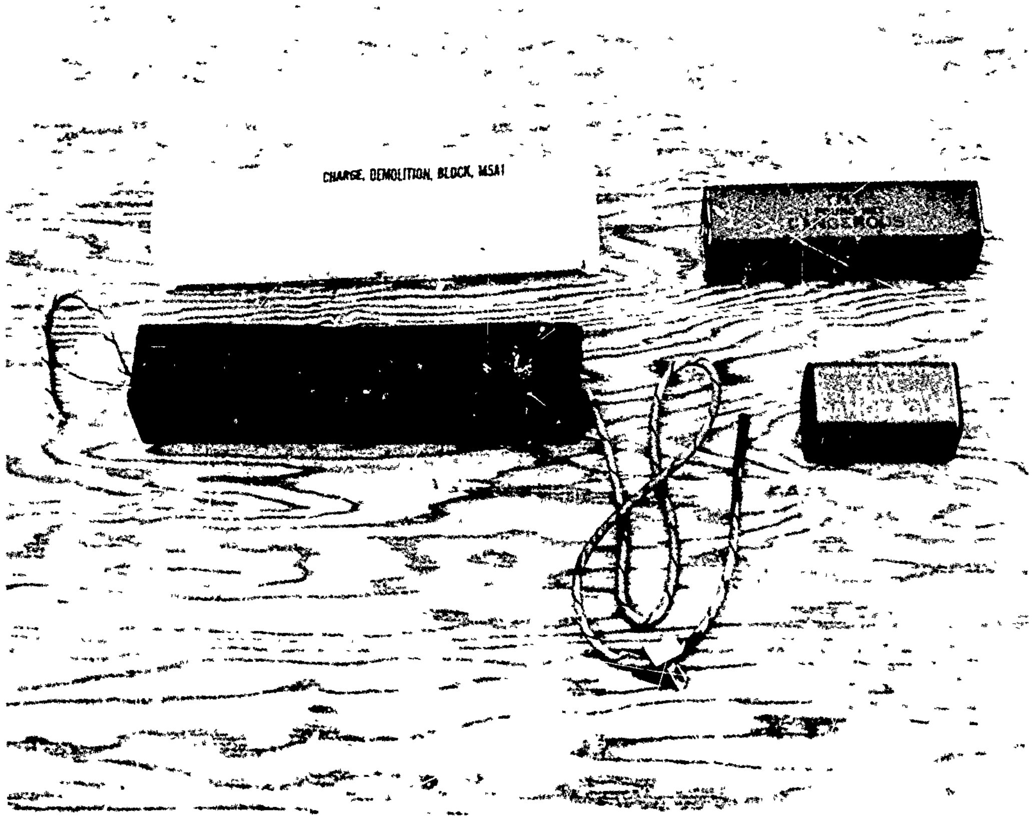
Fig. 4. Cross-fracture splits (at "y") and longitudinal split formed in steel from center-point detonation (at "x") of 1/2- by 2- by 11-inch contact explosive charge. (Note that spall is not split.)

4. Significance of Explosive Charge Dimensions. The force of an explosion is proportional to the quantity and power of explosive involved, but the destructive effect depends on the contact between the explosive and the target and on the manner that the explosive force is directed at the target. For maximum destructive effect against a steel target, an explosive charge with configuration and dimensions optimum for the size and shape of the target must be detonated in intimate contact with the steel along the desired line of cut. Any air or water gap between the explosive charge and the steel greatly reduces the cutting effect of the charge because the

destructive shock wave attentuates rapidly in those mediums, and close contact is essential for full shattering effect. An optimum relation must exist between the area of the charge in contact with the target and its thickness in order to transmit the greatest shock. If any given weight of explosive, calculated to cut a given target, is spread too thinly, there will be insufficient space for the detonation wave to attain full velocity before striking the target, and the shock wave will tend to travel more nearly parallel than normal to the surface over much of the area; the volume of the target will be excessive for the strength of the shock wave. At the other extreme, a thick charge with narrow contact area will transmit the shock wave over too little of the target and will also result in excessive lateral loss of energy (9)(10).

Steel-cutting experiments at SRI in 1957 disclosed that an explosive charge of minimum width and thickness was required to cut a given thickness of steel without waste of explosive (7). A strip of C-4 explosive 1/8 inch thick by 2 inches wide by 11 inches long, detonated on a 1-inch-thick steel plate, dented the top of the plate, and spalled the back side but did not cause either a longitudinal split or a cross fracture. As the charge thickness was increased, a thickness was reached where a partial longitudinal split and a partial cross fracture appeared. When the thickness of the charge was increased to 1/2 inch, the longitudinal split completely cut the plate and the cross fracture formed; the 1/2-inch-thick charge represented the minimum thickness of explosive required to cut the 1-inch steel plate. As the charge thickness was increased beyond 1/2 inch, the depression in the top of the plate became deeper, and the long split became wider. Charge thicknesses greater than 1-1/2 times the charge width had no additional destructive effect on the plate. By beginning with a strip of C-4 explosive 1/2 inch thick and 1/8 inch wide, the effect of varying the charge width was similarly revealed. With that extremely narrow charge, the only noticeable effect was a depression in the top of the plate; but, as the charge was widened, a width was reached where the back of the plate spalled. An explosive charge that had a 2-inch width split the plate under the length of the charge and produced the characteristic cross fracture.

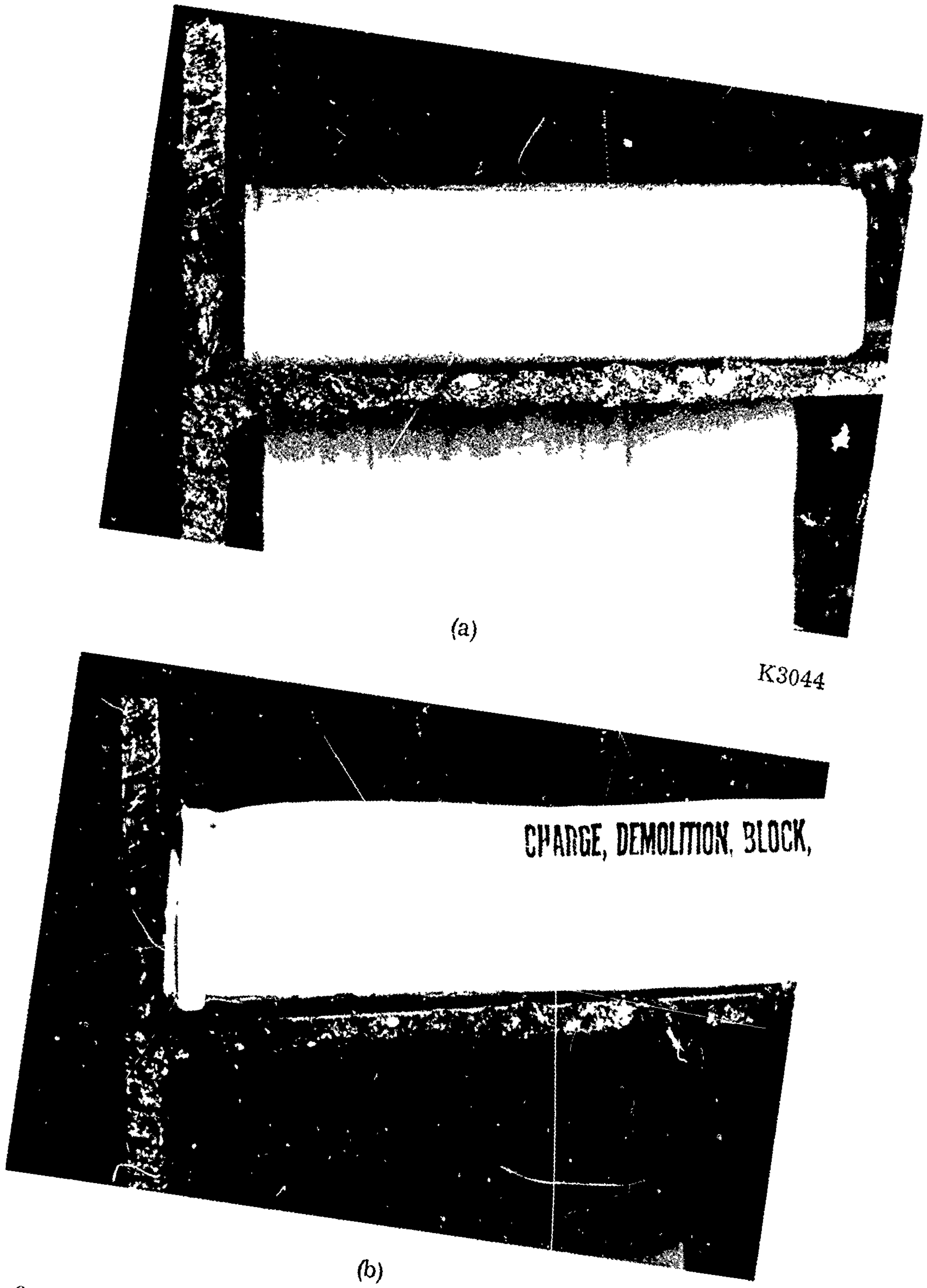
An optimum thickness and width, then, must exist for explosive charges required to cut various thicknesses of steel, but standard demolition blocks of explosive, except for the recently standardized M112 and M118 charges, seldom approach the optimum. U. S. Army blocks of explosive presently available for issue, such as the 2-1/2-pound Composition C-4 and Tetrytol charges and the 1/2- and 1-pound TNT blocks, have square cross sections that result in excessive waste of explosive because most structural steel targets can be cut effectively with rectangular charges about



K3040

Fig. 5. U. S. Army demolition blocks of high explosives. Top left, 2-1/2-pound block of C-4 explosive; bottom left, 2-1/2-pound block of Tetrytol; bottom right, 1/2-pound block of TNT; and top right, 1-pound TNT block.

one-half as thick (Fig. 5). Because of their inflexible form, U. S. Army explosive blocks are neither easily adaptable nor rapidly and simply attachable to the various shapes of steel targets. Excessive troop effort and time are required to fix charges of those blocks to even the most simple steel shapes. Close contact between presently available explosive blocks and the material to be demolished is virtually impossible to obtain without removing the explosive from its package, which is not feasible. Figure 6 shows air gaps between explosive blocks and the web and flange of a wide-flange steel beam where the fillet of the beam prevents close contact. This effect is more pronounced with rigid blocks of TNT and Tetrytol than with semirigid C-4 explosive blocks.



(a)

K3044

(b)

K3042

Fig. 6. Explosive blocks emplaced on steel beam; (a) TNT and (b) C-4.

II. INVESTIGATION

5. Characteristics of Test Explosives. Four kinds of high explosives were test fired and evaluated in this experimental program. Of the four high explosives tested, Composition C-4 was the only standard military explosive, EL506A-5 Detasheet flexible explosive was a commercial formulation, paste explosive was an experimental composition which was investigated for possible general demolition use, and aluminized paste explosive was manufactured by blending atomized aluminum powder with the paste explosive. Composition C-4 explosive served as a basis for comparison of the steel-cutting effectiveness of the other three explosives. Composition C-4 was also performance tested. Some of the characteristics of the four explosives are as follows:

a. Composition C-4 Explosive. Composition C-4, an RDX base plastic explosive, is white in color and has a density of about 1.57 grams per cubic centimeter as issued in a standard 2- by 2- by 11-inch block which weighs 2-1/2 pounds (3). In previous USAERDL tests, the detonating velocity of Composition C-4 explosive of the same lot as that used in these experiments was shown to be 26,000 feet per second at a density of 1.57 grams per cubic centimeter, the density of the C-4 explosive tested (11). Composition C-4 explosive is about a third more powerful than TNT, and although the packaged blocks of C-4 explosive are semirigid, the explosive is pliable and suitable for molding into almost any shape when it has been removed from the plastic wrapper. Molding or kneading of Composition C-4 explosive reduces its density with resulting reduction in its detonation velocity; reduction of its detonating velocity significantly reduces its brisance and power. The ingredients of Composition C-4 explosive are:

Ingredient		Percentage of C-4 Explosive
RDX		91.00
Polyisobutylene		2.10
Motor Oil		1.60
Di-(2-ethylhexyl) Sebacate		5.30
	Total	100.00

Because the weights and dimensions of the C-4 explosive charges for each test were closely controlled, a knife was used to cut the C-4 explosive blocks to the specified sizes without disturbing the explosive density.

b. Paste Explosive. The RDX base paste explosive used in this test program was manufactured by mixing bulk Composition C-4 explosive with DNT and MNT oils and Shell 40 thinner. It was a semifluid, oily explosive paste which had a density of 1.52 grams per cubic centimeter and a consistency of a light grease. The explosive and thinner oils exuded rapidly from the paste explosive and formed a pool on top of the explosive in the containers. For demolition of concrete, steel, and wooden targets, the explosive adheres more readily to the target surfaces if the oils are poured off prior to stirring of the paste explosive. The detonating velocity of the paste explosive used in these tests was determined by an electronic counter chronograph method on 10 explosive samples, 1 by 1 by 18 inches. The average rate of detonation for the samples was 24,466 feet per second. The dull-yellow paste explosive (Fig. 7) had ingredients as follows:

Ingredient	Percentage of Paste Explosive
RDX	76.44
DNT	4.89
MNT	3.26
Shell 40 Thinner (Tween)	7.85
Polyisobutylene	1.74
Motor Oil	1.36
Di-(2-ethylhexyl) Sebacate	4.46
Total	100.00

K3179

Fig. 7. Paste explosive in 100-pound container.

c. Aluminized Paste Explosive. Paste explosive was aluminized by adding 18 percent by weight of ALCO 120 atomized aluminum powder. The aluminum powder and paste explosive were intermixed at the field test site by dumping the two ingredients together in a wooden mortar box (no metal parts) and blending the compound with a hoe until a uniform mixture was obtained. Density of the aluminized paste explosive was slightly higher than that of paste explosive because much of the oil was apparently adsorbed by the finely divided aluminum powder; absorption of the oils adversely affected the adhesive characteristic of the explosive. Aluminized paste explosive was less plastic than paste explosive. However, as the aluminized paste explosive was less plastic than the paste explosive, slight tamping was required to form compact charges. In 10 rate-of-detonation tests in which an electronic counter chronograph method was used on 1- by 1- by 18-inch explosive samples, the average detonating velocity of the aluminized paste explosive was 23,079 feet per second or about 1,400 feet per second less than the detonating velocity of paste explosive. With a slower rate of detonation than paste explosive, the aluminized paste explosive had less shattering ability and was therefore less effective for steel cutting. After statistical analysis of experimental data from a factorial experiment had revealed that aluminizing the paste explosive did not increase its steel-cutting ability, the aluminized paste explosive was not evaluated further for cutting steel.

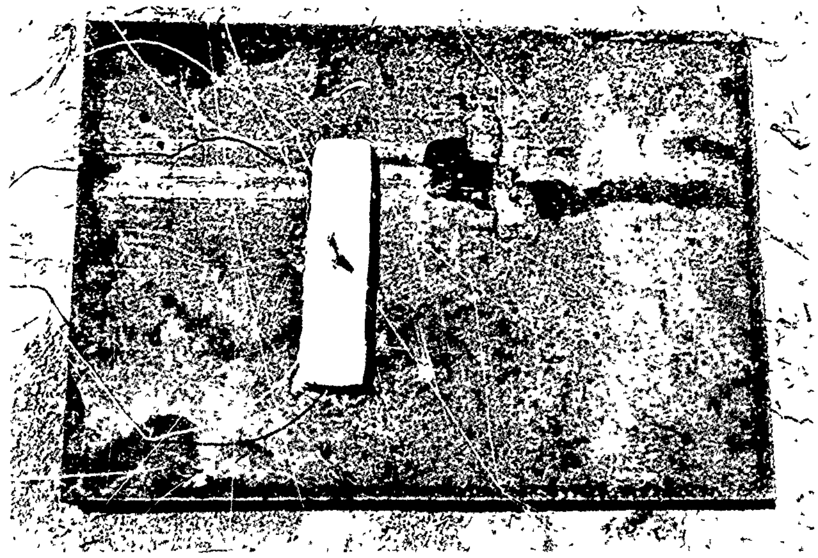
d. EL506A-5 Detasheet Flexible Explosive. A commercial formulation designated "Detasheet" by its developer, the flexible sheet explosive tested in this program was composed of an integral mixture of 85 percent PETN (pentalrythritol tetranitrate) and elastomeric binder that gave it flexibility and formability over a temperature range of 0 to 130° F. The 10- by 20-inch sheets of explosive were 0.207 inch thick with a density of 1.48 grams per cubic centimeter or 5 grams explosive weight per square inch, and had a detonating velocity of 23,616 feet per second. Colored red for identification, the EL506A-5 flexible sheet explosive was consistently detonated with the U. S. Army special blasting caps, J-1 nonelectric, J-2 electric, and M6 electric; the standard overhand knot in a 10-inch bight of detonating cord also reliably exploded the sheet explosive. A fixed blade knife was used to cut sheet explosive to the desired configurations, and multiple sheets were stacked vertically to obtain a desired charge thickness (Fig. 8). Detasheet flexible explosive of the EL506-A type tested was developed specifically for the velocity-impact hardening method of work-hardening castings made from manganese steel (12)(13). Detasheet C flexible explosive, a formulation that contains 63 percent PETN with pyrocellulose plasticized with Acetyl Tributyl Citrate, has been standardized for military use under Military Specification MIL-E-46676 (MU), "Flexible Explosive," and

K1615

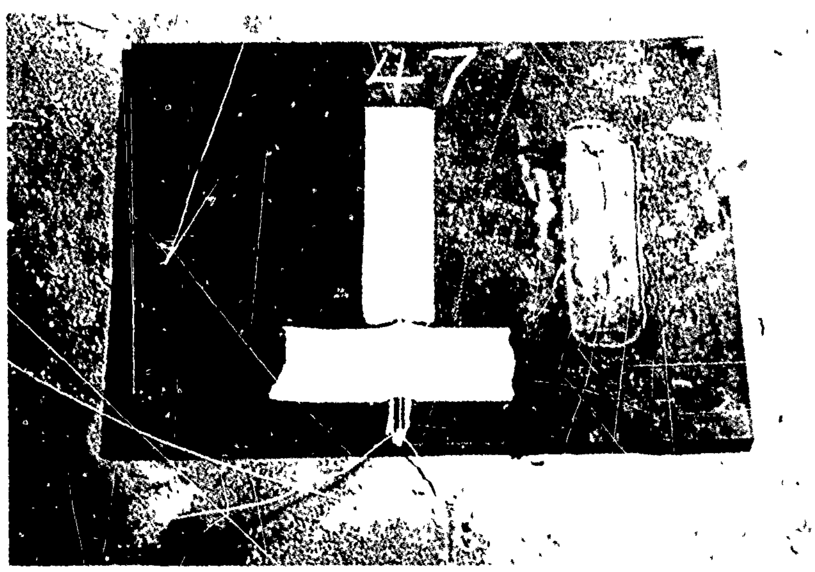
Fig. 8. EL506A-5 Detasheet flexible explosive.

will be issued as 1/4- by 3- by 12-inch sheets of 1/2-pound explosive weight; four sheets packaged in a Mylar container have been designated Charge, Demolition, M118, FSN: 1375-729-5941 DOD (M024).

6. Statistical Experiments. At the outset, four explosive tests each of which used a factorial experimental design were performed to determine, by statistical methods, the effects of types of explosives, charge widths and thicknesses, and points of initiation on the destructive power of contact explosive charges. A modification of the Ordnance Plate Dent Test, the factorial experiments measured the volumes of deformations made in mild steel plates by contact charges of Composition C-4, paste, and aluminized paste explosives in 1- to 2-inch widths detonated on the plates. Although no actual shattering or cutting of the steel plates was effected, detonation of the explosive charges against the steel plates produced a deformation in the charge side of the plates, which previous investigation had revealed to be related to the brisance of an explosive (4). Statistical analysis of variance, calculated on the volumes of the deformations revealed whether a significant difference existed among the variables of each experiment.

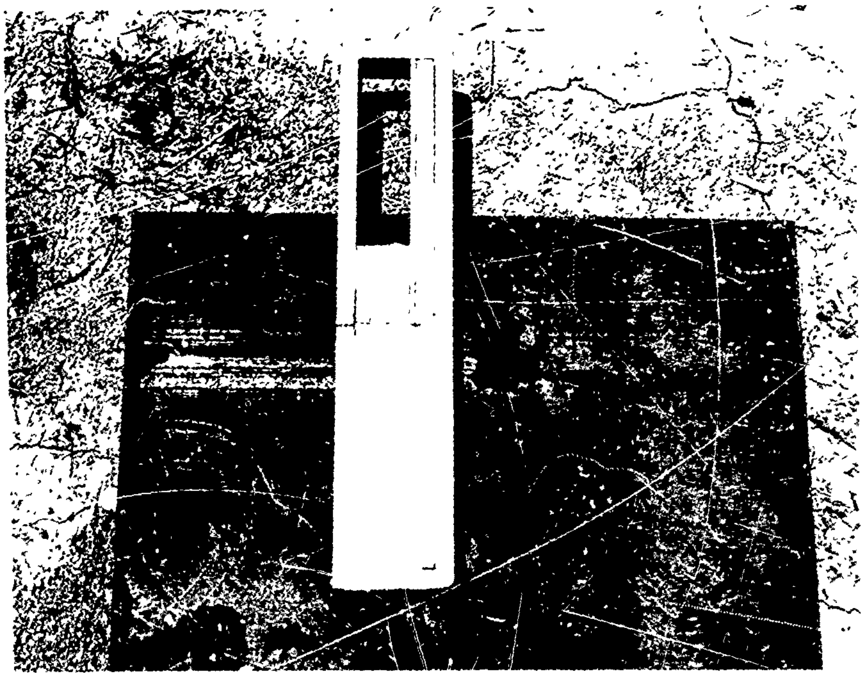


(a) J6493



(b) J6496

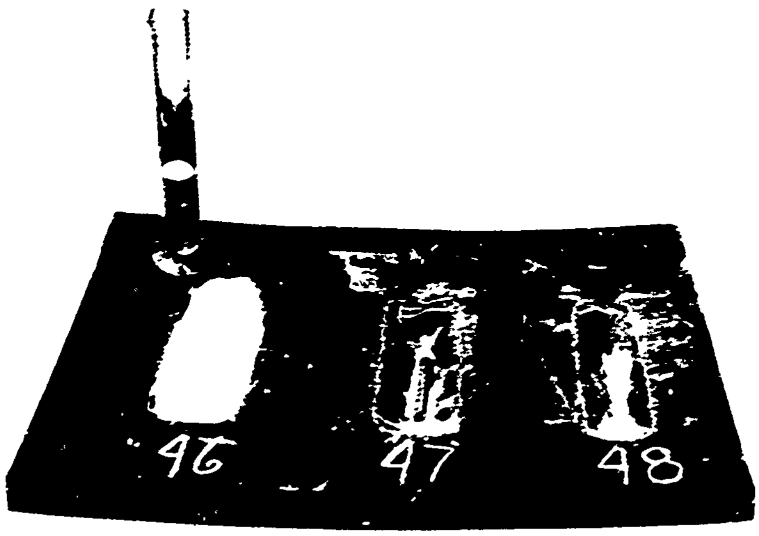
Fig. 9. Six-inch-long explosive charges of variable widths and thicknesses used in factorial experiments. (a) Paste explosive charge, center primed; and (b) C-4 charge, end primed.



J6495

Fig. 10. Use of wooden mold to fix dimensions of paste and aluminized paste explosive charges.

The four factorial experiments used uniform test procedures although the explosive charge parameters varied with experiments. Placed on 1- by 12- by 18-inch mild steel plates that were laid on level ground, 6-inch-long charges of paste, Composition C-4, and aluminized paste explosives deformed the solid steel plates after detonation took place at either the end or the center by U. S. Army special electric blasting caps (Fig. 9). A rectangular wooden mold with variable inside dimensions was used to fix and control the widths and thicknesses of the paste and aluminized paste explosive charges (Fig. 10). C-4 explosive charges were cut to the specified dimensions by means of a template and a knife. Blasting caps were butted against the explosive charges for detonation. Explosion of the charges deformed the charge side of the plate. These deformations were filled with Ottawa sand to the level of the undamaged plate surface, and the recorded quantity of sand in cubic centimeters was taken as the measurement of charge yield for the statistical analysis. Spall damage on the reverse side of the steel plate also provided a q , ititative indication of the significant explosive charge parameters (Fig. 11).



(a) J6492

(b) J6466

Fig. 11. Measurements of charge yields for factorial experiments. (a) Ottawa sand measures volume of charge deformation; and (b) spall damage on reverse side indicates variations in charge yields.

a. Experiment 1. This complete factorial experiment was conducted to determine the optimum of two types of explosives, two charge thicknesses, two points of charge initiation, and three charge widths. The factors and their levels are presented in Appendix L to this report. Forty-eight charges were detonated in random order in 48 test firings.

Although not considered a factor in the experiment, the charge weights also varied in the relation to the differences in the charge widths and thicknesses. As can be seen in the analysis of the experimental results, the differences in weights of explosive charges did not affect the charge yields as significantly as did the widths and thicknesses of the charges. Listed in descending order of magnitude, charge yields are given in Table II as the volumes in cubic centimeters of the deformations in the steel plates. The charge parameters are also given.

Attached as Appendix B, a statistical analysis of variance, calculated on the charge yields, revealed that the type of explosive, thickness of charge, and width of charge were all highly significant. The fourth factor, the point of initiation of the charge, was not significant. With both the paste and C-4 explosives, as revealed by the volumes of the charge yields in Table II, the charges of 1-inch thicknesses and 2-inch widths produced the largest deformations in the steel plates. One would expect those 1- by 2- by 6-inch charges to displace a larger volume of steel, though, because they contained about one-third more explosive and had a larger contact area with the steel than the 1- by 1-3/8- by 6-inch charges. But these results demonstrate that there is an optimum ratio of charge thickness to the contact area of the target (Figs. 12 and 13).

On the basis of the results with 1- by 2- by 6-inch charges, then, the 1- by 1-3/8- by 6-inch charges of paste and C-4 explosives would be expected to react normally and give greater yields than the 1/2- by 2- by 6-inch charges of about one third less explosive and contact area, but this was not so. The 1/2- by 2- by 6-inch charges produced deformations in the steel plates with volumes equal to those of the 1- by 1-3/8- by 6-inch charges which indicated that the optimum ratio of charge width to charge thickness was between 2:1 and 4:1. The variations in explosive weights among the different sizes of charges introduced bias into the test data; however, as the analyses of variance of the charge yields from experiments 2 through 4 showed, variations in charge widths and thicknesses had more pronounced effects on yields of steel-cutting explosive charges than did variations in explosive quantities. Moreover, test personnel expected C-4 explosive charges to give significantly larger yields than paste explosive charges. This effect occurred because C-4 had considerably faster

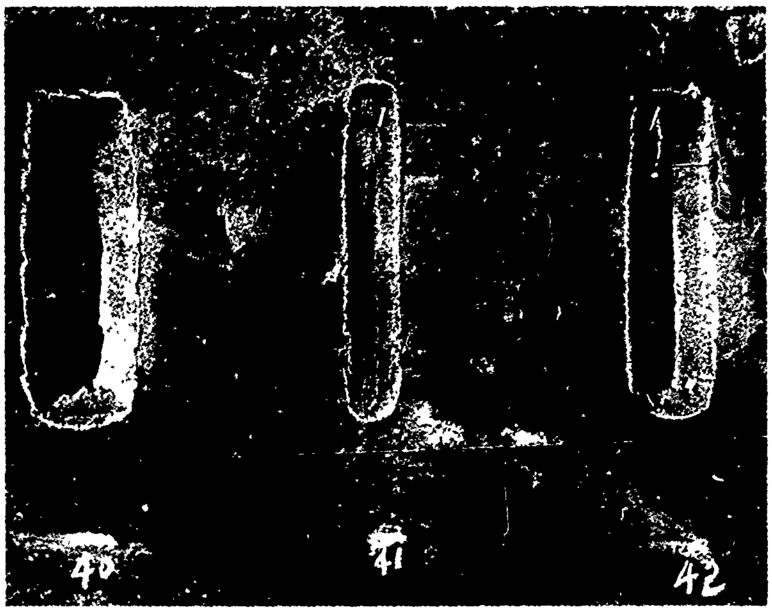
Table II. Test Data for Factorial Experiment 1

Paste Explosive Charge						Composition C-4 Explosive Charge					
Test Shot	Weight (g)	Dimension (in.) Thickness	Dimension (in.) Width	Point of Initiation	Result - Volume of Charge Yield (cc)	Test Shot	Weight (g)	Dimension (in.) Thickness	Dimension (in.) Width	Point of Initiation	Result - Volume of Charge Yield (cc)
5	320	1	2	Center	83.0	40	317	1	2	End	88.0
3	309	1	2	End	80.4	43	315	1	2	Center	76.5
10	314	1	2	End	72.0	46	312	1	2	Center	76.0
9	312	1	2	Center	70.0	47	321	1	2	End	67.0
12	214	1	1-3/8	Center	34.5	34	168	1/2	2	Center	48.5
2	216	1	1-3/8	End	31.4	39	224	1	1-3/8	Center	48.0
17	175	1/2	2	Center	30.5	48	234	1	1-3/8	End	43.5
22	151	1/2	2	Center	30.0	35	163	1/2	2	Center	42.0
7	213	1	1-3/8	End	30.0	28	170	1/2	2	End	40.0
16	165	1/2	2	End	28.6	30	162	1/2	2	End	40.0
4	202	1	1-3/8	Center	27.0	13	230	1	1-3/8	Center	37.0
25	147	1/2	2	End	24.0	42	229	1	1-3/8	End	31.0
18	109	1/2	1-3/8	End	18.0	31	115	1/2	1-3/8	Center	23.5
23	122	1/2	1-3/8	End	17.2	32	110	1/2	1-3/8	End	21.5
19	117	1/2	1-3/8	Center	15.7	27	114	1/2	1-3/8	End	21.0
20	117	1/2	1-3/8	Center	15.2	33	101	1/2	1-3/8	Center	17.5
6	123	1	3/4	Center	9.0	45	119	1	3/4	Center	17.0
11	121	1	3/4	Center	9.0	41	118	1	3/4	Center	11.0
8	117	1	3/4	End	8.2	44	119	1	3/4	End	10.0
1	116	1	3/4	End	7.2	36	61	1/2	3/4	End	10.0
14	75	1/2	3/4	End	7.0	37	62	1/2	3/4	Center	9.0
24	64	1/2	3/4	Center	7.0	29	66	1/2	3/4	End	8.0
15	67	1/2	3/4	Center	6.0	38	110	1	3/4	End	8.0
21	61	1/2	3/4	End	5.0	26	62	1/2	3/4	Center	7.0

J6459

J6458

Fig. 12. Effects of variations of charge widths on shattering power of paste explosive charges (charge widths were 2 inches for test shot 5, 1-3/8 inches for test shot 4, and 3/4 inch for test shot 6. Thicknesses for all charges were 1 inch).



J6479

J6478

Fig. 13. Effects of variations of charge widths on shattering power of C-4 explosive charges (charge widths were 2 inches for test shot 40, 3/4 inch for test shot 41, and 1-3/8 inches for test shot 42. Thicknesses for all were 1 inch).

detonating velocity and greater density than did the paste explosive. The brisance or shattering ability of explosives, an important characteristic for steel cutting, is related to their rates of detonation and densities.

b. Experiment 2. To substantiate the findings of experiment 1 as to the significance of explosive thicknesses and widths for steel-cutting charges, a one-factor, five-level factorial experiment was performed with paste explosive charges of 84-gram weight. Exactly the same quantity of explosive was used but the widths and thicknesses of the charges were varied; therefore, it was expected, not only to verify the results of experiment 1, but also to reveal more emphatically the great effect of charge widths and thicknesses on the destructive power of contact explosive charges. Paste explosive charges of 6 inches in length and of 1, 1-1/4, 1-1/2, 1-3/4, and 2 inches in width were detonated on 3/4-inch mild steel plates. U. S. Army special electric blasting caps initiated all charges at one end because experiment 1 had showed the insignificance of point of initiation. Charge widths were closely controlled but, as the same amount of explosive was used for all charges, the charge thicknesses decreased as the charge widths increased. With three replicates of the five different charge widths, 15 test firings comprised the one-factor experiment. Table III lists the charge variables and test results with the volumes of the deformations in the steel plates arranged in descending order of yields.

Table III. Test Data for Factorial Experiment 2

Test Shot	Charge Width (in.)	Volume of Charge Yield (cc)
9	2	23.5
1	2	19.0
12	1-3/4	20.5
6	1-3/4	20.0
3	1-3/4	18.5
15	1-1/2	18.0
14	2	17.5
4	1-1/2	17.0
2	1-1/4	15.0
8	1-1/2	14.0
10	1-1/4	13.0
13	1-1/4	11.0
7	1	12.0
5	1	10.0
11	1	9.5

Note: The only type of explosive used in testing was paste.

The analysis of variance performed on the volumes of the deformation in the steel plates again showed that the width of the explosive charge had a significant effect on the size of the depressions. But there were more than two levels of charge width, so Tukey's method of simultaneous confidence intervals was applied in order to find which pairs of charge widths were significantly different from the others (15). Appendix B shows that the 1-inch charge width was significantly less effective than the 1-1/2-, 1-3/4-, and 2-inch charge widths, and the 1-1/4-inch charge width differed significantly in destructive effect from the 1-3/4- and 2-inch charge widths. Hence, the 1-1/2-inch charge width was more effective than the 1-inch charge width but was not measurably better than the 1-1/4-inch charge width. Moreover, the 1-3/4- and 2-inch charge widths, although considerably more destructive than the 1-1/4-inch charge width, were not significantly more effective than the 1-1/2-inch charge width. A simple arithmetical average of the volumes of charge yields show 20 for the 2-inch width, 19-2/3 for the 1-3/4-inch width, and 16-1/3 for the 1-1/2-inch width.

The test results, therefore, again illustrate that there is an optimum ratio of charge width to charge thickness for contact explosive charges used to cut given thicknesses of steel. If the charge is too thick in relation to its width, insufficient explosive force will be imparted against too small an area of the steel to cut it. The opposite effect will be true if the explosive charge is too thin in relation to its width. Thin charges of excessive width will transmit insufficient explosive shock over too great an area so that the steel will likewise not be cut. Subsequent data showed that the optimum ratio of charge width to charge thickness was about 3:1 for contact explosive charges to cut steel.

c. Experiment 3. This two-factor experiment with two levels of each factor was conducted primarily to determine the effectiveness of aluminized paste explosive for steel cutting. As a secondary experimental objective, the charges were initiated at the center so that the data from the experiment could be combined with those from experiment 2, in which the charges were initiated at the end, to form experiment 4 that again evaluated the effect of point of charge initiation. With 84 grams of explosive in 6-inch charges of 1- and 2-inch widths, the complete factorial experiment had three replicates of each factor combination which made 12 test shots. The experimental factors and their charge yields are given in Table IV:

Table IV. Test Data for Factorial Experiment 3

Test Shot	Type of Explosive	Charge Width (in.)	Volume of Charge Yield (cc)
1	Paste	2	22
6	Paste	2	20
9	Aluminized Paste	2	20
7	Aluminized Paste	2	19
10	Paste	2	17
4	Aluminized Paste	2	17
12	Paste	1	14
3	Paste	1	12
8	Paste	1	8
2	Aluminized Paste	1	7
11	Aluminized Paste	1	7
5	Aluminized Paste	1	6

When the statistical analysis of variance was calculated from the test results from experiment 3, the 2-inch charge width was found to be significantly better than the 1-inch charge width, but the type of explosive was not significant. Aluminizing the paste explosive did not increase its shattering ability, which was a requisite for improved steel-cutting ability. On the basis of an arithmetical average, the aluminized paste explosive gave averaged yields for the six test shots that were slightly below those of the paste explosive. However, the difference was so small that it was insignificant as revealed in the statistical analysis in Appendix B.

d. Experiment 4. Test results from experiments 2 and 3 were combined to provide data for this experiment. By combining the test results from 1- and 2-inch charge widths of experiment 2, which were initiated at the end, with results from similar charge widths initiated at the center in experiment 3, data for a two-factor, two-level, complete factorial experiment were available for an analysis of variance. The factors considered were point of charge initiation, end and center, and charge widths, 1 and 2 inches, so with 3 replicates, 12 sets of experimental data listed in Table V were analyzed.

Calculated on the volumes of the charge yields, which were the measured volumes of the charge-deformed depressions in the steel plates, the analysis of variance revealed that the 2-inch charge widths

Table V. Test Data for Factorial Experiment 4

Charge Width (in.)	Point of Charge Initiation	Volume of Charge Yield (cc)
2	End	23.5
2	Center	22.0
2	Center	20.0
2	End	19.0
2	End	17.5
2	Center	17.0
1	Center	14.0
1	Center	12.0
1	End	12.0
1	End	10.0
1	End	9.5
1	Center	8.0

Note: The type of explosive used in testing was paste.

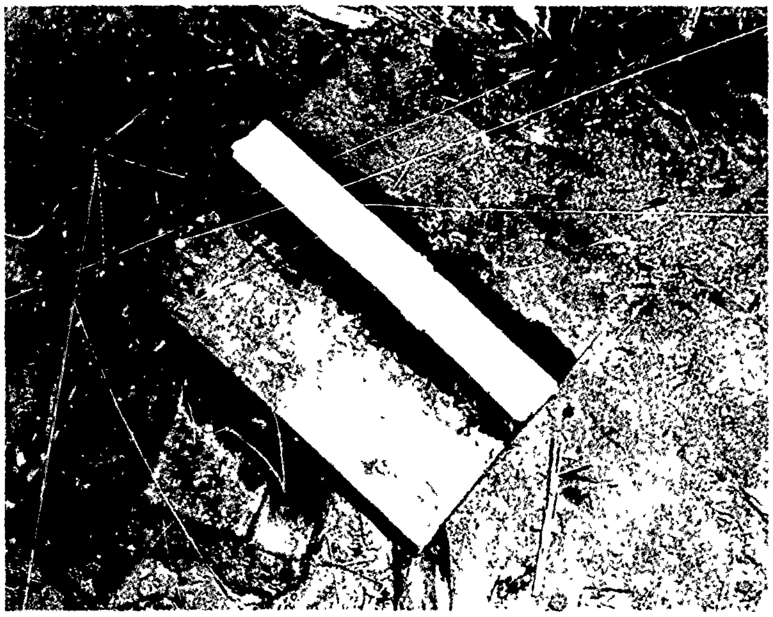
produced significantly larger deformations than the 1-inch charge width. The statistical analysis again showed that the point of charge initiation had no significant effect on charge yields. But, although the point of initiation does not enhance the magnitude of explosive shock from a detonating explosive charge and is unimportant when steel plates are being cut, successful explosive cutting of steel bars and structural steel beams with contact charges requires charge initiation at specific points. In experiments described in this report, the point of charge initiation also proved to be an essential element in the stress wave technique of steel cutting with explosives.

7. Explosive-Cutting Tests on Steel Plates. Ninety-eight experiments were performed to determine the optimum size charges of Composition C-4, paste, and Detasheet explosives for cutting 1/4- to 3-inch steel plates. Composition C-4 and paste explosives were evaluated in 49 test shots on 1/4- to 1-inch-thick mild steel plates of 12-inch lengths. A number of experimental firings were made to test Composition C-4 and Detasheet explosives on 18-inch-long plates of 1/4- to 1-inch-thick mild steel and 3-inch-thick alloy steel.

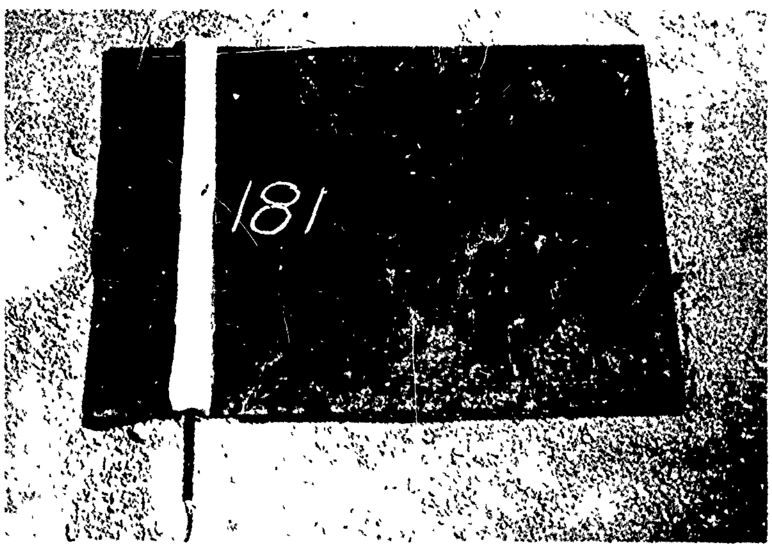
a. Test Procedures. Evaluation of the three kinds of high explosives for cutting steel plates involved several techniques of charge calculation, placement, and detonation. For analytical comparison, the

U. S. Army steel-cutting formula $P = \frac{3/8\,A}{1.34}$ determined the quantities of explosive that troops would normally use to cut the steel plates in each test. The SRI steel-cutting formula, charge thickness = 1/2 steel thickness plus 1/8, charge width = 4 times the charge thickness, and charge length = length of steel to be cut (SRI formula is $C_T = 1/2\ S_T + 1/8$, $C_W = 4\ C_T$), served as a guide for computation of actual charges of C-4 and paste explosives used in the first 49 test shots on 12-inch-long mild steel plates of 1/4- to 1-inch thicknesses. A modification of the SRI formula, $C_T = 1/2\ S_T$, $C_W = 3\ C_T$, was used to compute the charges of C-4 and Detasheet explosives detonated on the 18-inch-long mild steel plates of 1/4- to 1-inch thicknesses and alloy steel of 3-inch thickness. Optimum sizes of charges for the various steel thicknesses were identified and verified through experimentation. Composition C-4 and Detasheet explosive charges were cut to the desired dimensions and then placed in intimate contact with the surface of the steel plate along the desired line of cut. Paste explosive charges were either extruded with a modified caulking gun or hand placed on to the steel plates in the approximate dimensions and then shaped or cut to more exact dimensions. Configurational dimensions of these rectangular charges, therefore, were not exactly uniform, especially those of the paste explosive, but the charge weights were accurate to the nearest gram. U. S. Army special electric blasting caps, with base ends either butted against or slightly embedded in the explosive, initiated 59 of the charges at the center and initiated the other 39 charges at the end (Fig. 14).

In the summary of explosive-cutting test results on steel plates presented in Appendix C, the details for each test shot are listed. These include dimensions and cross-sectional areas of the steel plates, weights, and dimensions of the explosive charges, as well as a comparison of the actual test quantities of explosive with the amounts calculated by the U. S. Army steel-cutting formula. Identified by test shot numbers which began with one and ended with 336, the first 49 experimental charges of C-4 and paste explosives were detonated on 12-inch-long mild steel plates that were laid directly on the ground. As the analysis of experimental data later disclosed, results of those tests were biased because of the adverse effect of the contact surface between the steel and soil which hindered spalling by transmitting explosive energy into the soil. Therefore, 49 charges of C-4 and Detasheet explosives were detonated on 18-inch-long alloy and mild steel plates that were laid on raised end supports so that the test plates had free surfaces opposite the explosive charges. These unbiased test shots in which all charges were initiated at the center are numbered from 339 to 394 in Appendix C.



(a) K3264

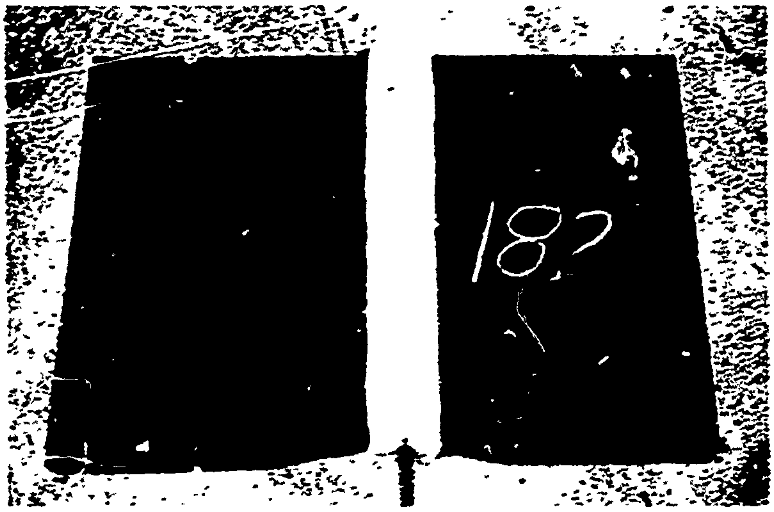


(b) J6608

Fig. 14. Rectangular explosive charges emplaced to cut 1- by 12- by 18-inch steel plates: (a) 1.37-pound C-4 explosive charge of 1 by 2 by 12 inches; and (b) 1/2-pound paste explosive charge of 3/4 by 1 by 12 inches.

b. Test Results. Of the 49 experimental charges of Composition C-4 and paste explosives detonated on mild steel plates laid directly on soil, 23 of the 40 paste explosive charges and 7 of the 9 C-4 explosive charges completely cut the 12-inch-long steel plates (Appendix C). In field operations, the two incomplete cuts with the C-4 explosive would have failed the steel plates because only one linear inch of steel remained uncut (test shots 332 and 336); however, in these tests a plate was considered uncut unless it had been completely severed. The seven C-4 explosive charges that severed the steel plates contained only 29 to 42 percent of the explosive calculated by the U. S. Army steel-cutting formula. Insufficient explosive in too narrow charge widths (26 percent of the calculated amount in 1-inch width and 20 percent in 1/2-inch width) caused the two incomplete cuts with the C-4 explosive. Three of the seventeen failures with paste explosive lacked only 1-1/2 to 2 inches of completely severing the steel plates. Although these 17 charges contained only 15 to 58 percent of the explosive calculated by the formulas, their failure to cut the plates is attributed to narrow charge widths, low-density charges, and to the steel plates that were laid on the ground; this feature interfered with the spalling of the steel from the reflected shock wave. Because the soil formed a backing on the steel surface opposite the charge side of the plate, much of the explosive energy was evidently transmitted into the soil; so the remainder reflected as a tension pulse was apparently too weak to spall the plates completely and form the longitudinal crack that normally fails steel targets (Fig. 15)(2). More explosive charges than usual were required to cut the plates (Fig. 16). These should have been set up so that normal spalling and fracturing could have occurred. Despite the adverse effect of the soil-steel contact surface which dissipated explosive energy, paste explosive charges of only 16 to 66 percent of the calculated amounts effectively cut the steel plates.

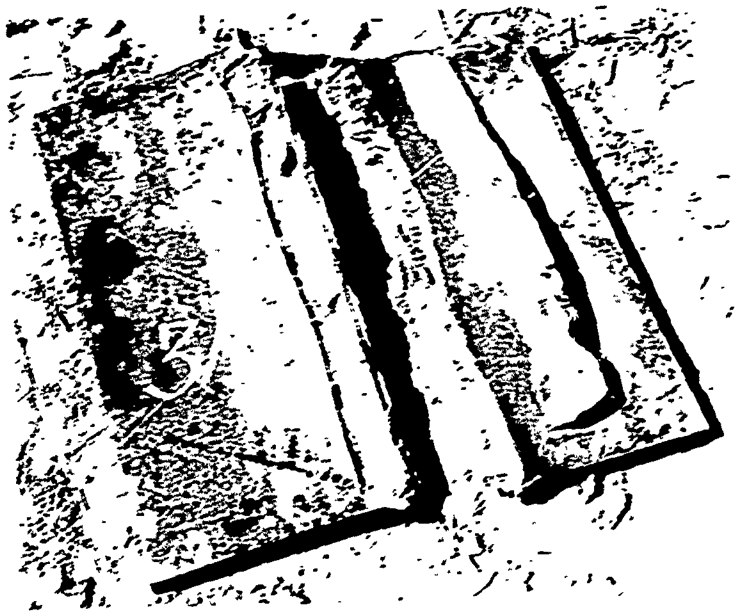
Results of the 49 C-4 and Detasheet explosive charges detonated on both alloy and mild steel plates that had free surfaces opposite the charge sides of the plates showed 43 complete cuts and 6 incomplete cuts (test shots 339 to 394 in Appendix C). Two EL506A-5 Detasheet explosive charges and one C-4 charge, 1/4 by 3/4 by 18 inches, failed to sever completely 1/2-inch-thick steel plates, and a 1/8- by 3/8- by 18-inch Detasheet charge and a 1/4- by 1/2- by 18-inch C-4 charge did not completely cut 1/4-inch-thick steel plates. These five failures were attributed to weaker shattering effects of the charges at the points of detonation because only about 3 inches of steel remained uncut at the plate centers precisely under the points where the blasting caps initiated the charges (Fig. 17). The blasting caps were slightly embedded into the 1/4-inch-thick charges, so less than 1/4 inch of explosive was between the base end of the blasting caps and the steel. On subsequent test shots when the explosive thicknesses



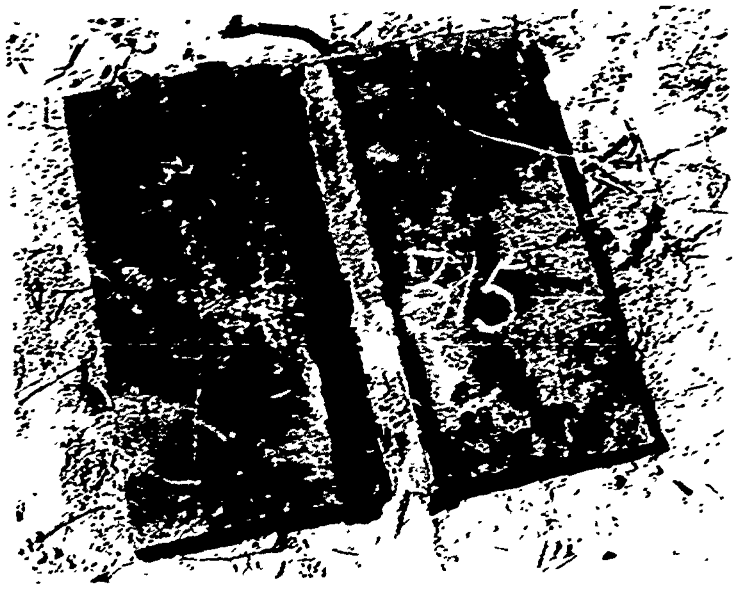
(a) J6607

(b) J6614

Fig. 15. One-inch mild steel plate not cut by: (a) 1/2 pound of paste explosive in 3/4- by 1- by 12-inch charge (test shot 181 at left in both photographs), and (b) 2, pound of paste explosive in 1/2- by 2- by 12-inch charge (test shot 182).

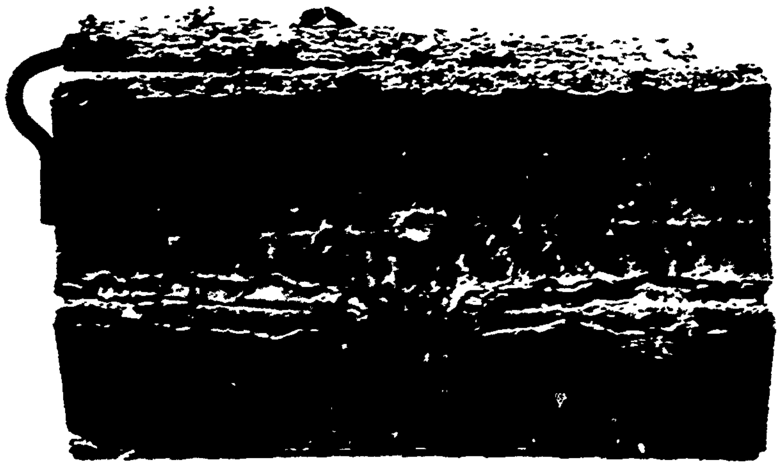


(a) K3267



(b) K3266

Fig. 16. One-inch mild steel plate severed by: (a) 1-1 3 pound of C-4 explosive charge of 1 by 2 by 12 inches; and (b) longitudinal split shown at center of charge deformed area in steel plate.



M5045

Fig. 17. Steel plate uncut at center under point of cap initiation of 1/4-inch-thick explosive charge.

were increased to 1/4 inch under the blasting cap at the point of initiation, the plates were completely cut. Finally, the sixth incomplete cut occurred on a 3-inch-thick alloy steel plate and was the result of insufficient explosive in a less than normal density charge (test shot 387 in Appendix C) and not of nonoptimum charge dimensions. As only about 1/8-inch thickness of steel was uncut, the steel plate would likely have failed if it had been part of a load-supporting structure.

The 49 Detasheet and C-4 explosive charges fabricated to specifications prescribed by the modified formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$, then, yielded complete cuts on 18-inch-long plates of 1/4- to 1-inch-thick mild steel and 3-inch-thick alloy steel with about 88-percent reliability which included the six failures, five from faulty priming and initiation and one from a low-density charge. But when the charges were 1/2 inch thick for C-4 explosive and 1/4 inch thick for EL506A-5 Detasheet explosive built up to 1/2 inch at the point of initiation, the percentage of reliability was 100 percent.

8. Explosive-Cutting Tests on Structural Steel Shapes. To find the optimum configuration, size, and detonating system for contact explosive charges to cut regular series shapes of structural steel, 139 experimental

charges of paste, C-4, and EL506A-5 Detasheet explosives were evaluated on steel angles, channels, and wide-flange beams of standard American design (15). The following paragraphs describe the test firings, experimental procedures, and results of this phase of the investigation.

a. Experiments on Steel Angles. Eighteen charges of paste, Composition C-4, and EL506A-5 Detasheet explosives were detonated on standard steel angles of 5- by 3-1/2-inch and 4- by 3-1/2-inch unequal legs and of 8- by 8-inch equal legs. The 5- by 3-1/2-inch angle had a cross-sectional area of 2.06 square inches, the 4- by 3-1/2-inch angle had an area of 2.67 square inches, and the 8- by 8-inch angle had a cross-sectional area of 16.73 square inches. Test firing of the ten paste explosive charges, four C-4 charges, and four EL506A-5 explosive charges were performed as follows:

(1) Procedure. Although both the U. S. Army and the SRI steel-cutting formulas were used to calculate the required charges, the SRI and a slight modification of it were used to establish the dimensions of the actual experimental charges. Those formulas were applied, and the calculated and actual charges for the 8- by 8-inch angle of 1-1/8-inch thickness and 16.73-square inch cross section were:

U. S. Army formula $$P = \frac{3/8\ A}{1.34}$$

$$P = \frac{(0.375)\ (16.73)}{1.34} = 4.68 \text{ pounds of}$$

explosive, either paste, C-4, or EL506A-5 Detasheet explosives because the relative effectiveness factor for C-4 explosive was also applied to the other two high explosives. In the U. S. Army steel-cutting formula, only the cross-sectional area of a steel member is considered and a required charge in pounds of explosive only is given; charge placement is an independent factor as is steel thickness except for its use to determine the cross section of the member.

SRI formula $CT = 1/2\ S_T + 1/8$

$C_W = 4\ C_T$

Charge length = length of steel to be

cut, where C_T = charge thickness, S_T = steel thickness, and C_W = charge width. Therefore

$$C_T = 1/2\ (9/8) + 1/8 = 11/16 \text{ inch}$$

$$C_W = 4\ (11/16) = 2\text{-}3/4 \text{ inches,}$$

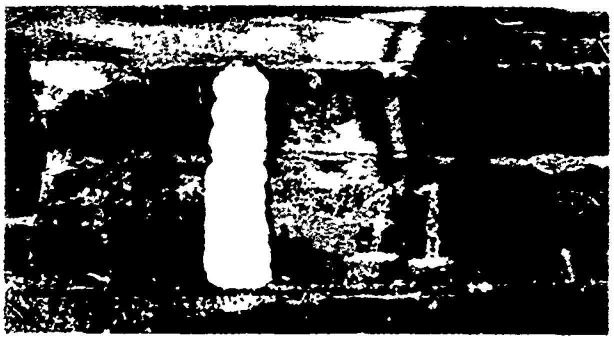
so an 11/16-inch-thick by 2-3/4-inch-wide by 16-inch-long charge was required. As determined by this method, the actual charges weighed about 1 to 1-1/3 pounds for paste explosive, 1-1/3 to 1-1/2 pounds for C-4 explosive, and 1-1/8 pounds for the EL506A-5 Detasheet explosive. Detailed characteristics of the experimental charges and the steel angles are presented in the summary of explosive-cutting test results in Appendix C. The charges used on the steel angles with unequal legs were thicker and wider than normal to insure detonation. In test shots 219 through 222 and 223b through d, thinner charges were employed because the SRI formula was modified to

$$C_T = 1/2\ S_T,$$

the plus 1/8 was dropped, and the charge width was unchanged.

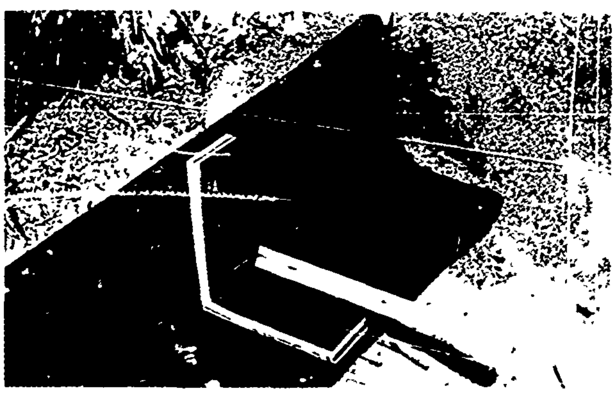
All charges were placed and detonated on the inside of the steel angles. Composition C-4 and EL506A-5 Detasheet explosive charges were cut to the specified dimensions and placed and taped firmly against the inside of the steel angle so that the explosive and the steel were in close contact along the desired line of cut. Paste explosive charges were either extruded on to the inside of the angle by a modified caulking gun or were hand placed in a similar position. Either way, a knife or spatula was used to shape or cut the paste explosive to the desired charge configurations, which needed no fastening because the paste adhered to the steel. U. S. Army special electric blasting caps primed and detonated all charges but two at the center; one C-4 charge and one paste explosive charge were initiated at one end (Fig. 18).

(2) Results. All 18 charges of the three kinds of explosives effectively cut the steel angles (Appendix C). Paste explosive charges of only 31 to 65 percent of the explosive calculated by the U. S. Army formula completely severed the unequal leg angles. Cutting of the 8- by 8-inch steel angle expended but 21 to 28 percent of the calculated charges for paste explosive, 27 to 32 percent for C-4 explosive, and 24 percent for EL506A-5 Detasheet explosive. These



(a) J5192

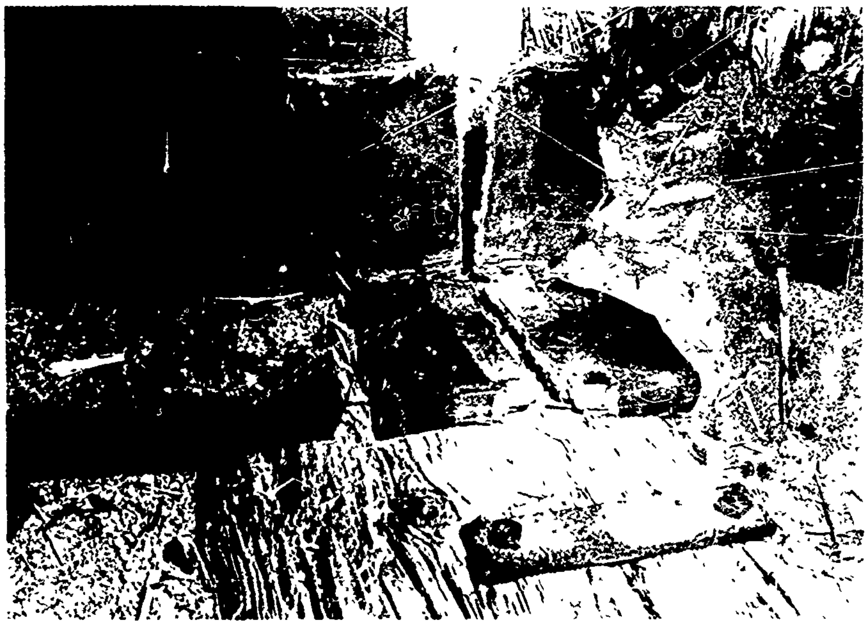
(b) K1635



(c) K1628

Fig. 18. Experimental explosive charges on steel angles. (a) Extruded paste explosive charge; (b) hand-placed charge of paste explosive, end-primed; and (c) charge of EL506A-5 Detasheet explosive.

percentages indicate a simple comparison of the explosive charge weights used in the test program to cut the angles and are not a comparative indication of the steel-cutting effectiveness of the three explosives. Because its form in thin sheets permitted the use of more exact charge thicknesses, less EL506A-5 explosive was used than the amount employed in more dense paste or C-4 explosives, which were difficult to shape and cut to precisely uniform thicknesses. None of the experimental charges represented the optimum or minimum for cutting the steel angles. Results showed overcharges especially with C-4 explosive (Fig. 19).



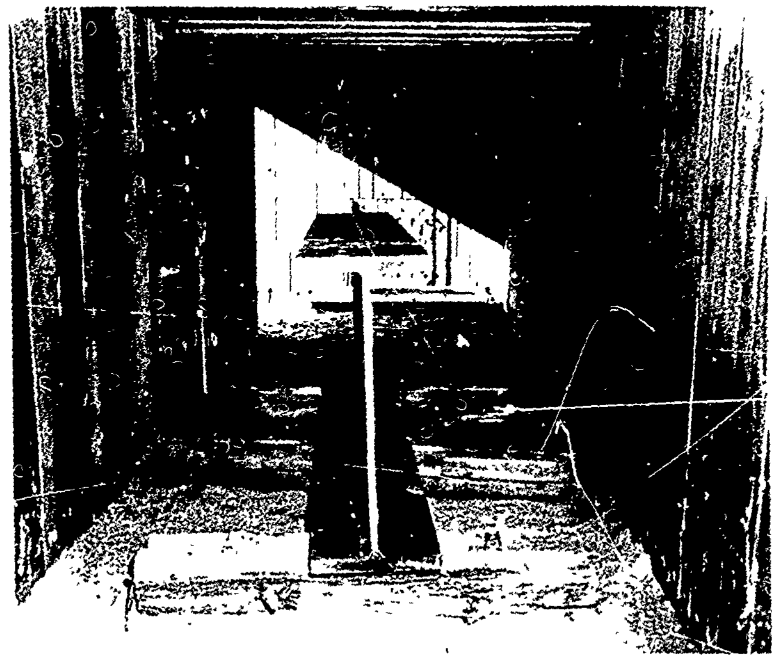
K1630

Fig. 19. Cutting effect of contact explosive charge on steel angle.

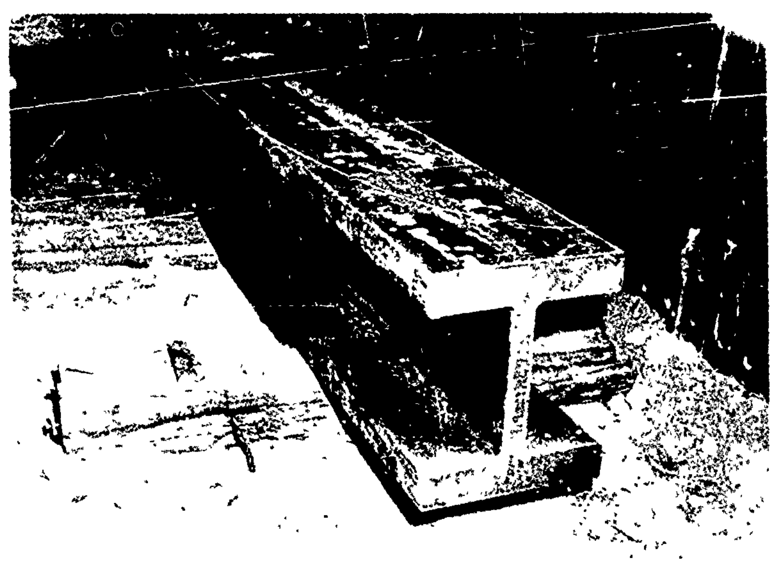
b. Experiments on Wide-Flange Steel Beams. One hundred and six test firings of paste, C-4, and EL506A-5 Detasheet explosive charges on wide-flange steel beams comprised the major portion of the steel-cutting experimental program. Because explosive cutting of wide-flange steel beams requires the combined severing of two wide flanges and a connecting web of depth normally exceeding the flange width, the applied demolition technique usually involves the placement and simultaneous detonation of two or three charges in order to cut the web and the flanges on both sides of a beam with one blast. Thus, during this phase of the explosive steel-cutting investigation, conducted on steel beams commonly encountered in bridge demolitions, charge placement, priming, and firing techniques as well as three kinds of high explosives were evaluated. The steel beam specimens and the explosive demolition methods tested are described in subsequent paragraphs. In these tests, only completely severed beams were considered satisfactory demolitions.

(1) Steel Test Beams. Six different sizes of wide-flange steel beams, which were regular series members commonly stocked for immediate delivery, were used as the test specimens. These were 16WF50, 10WF49, 14WF74, 24WF76, 36WF300, and 14WF426 beams; the designation of wide-flange beams identifies them as wide-flange type as opposed to the American standard I-beam and gives their overall depth and weight in pounds per linear foot. Hence, the designation 36WF300 specifies a wide-flange beam of 36-inch depth that weighs 300 pounds per linear foot (Fig. 20). Specific details of the six types of test beams are given in the summary of explosive-cutting test results on steel beams and channels in Appendix C.

(2) Charge Calculations. For comparison of calculated explosive charge weights with actual quantities of explosive used in test firings, the author again utilized the U. S. Army steel-cutting formula $P = \frac{3/8\ A}{1.34}$ and the SRI formula $C_T = 1/2\ S_T + 1/8$, $C_W = 4\ C_T$. The latter formula was used to compute the actual charges initially, as has already been described for both formulas. When numerous explosive charges calculated by the SRI formula had successfully cut 16WF50 and 10WF49 beams of 14.7- and 14.4-square inch cross-sectional areas, respectively, modifications of that formula were applied in an effort to optimize the charge sizes and configurations. Because charges of smaller dimensions than called for by the SRI formula had completely cut the steel test beams, beginning with test shot 87, the modified formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ was used to compute the size of the charges (C_T = charge thickness in inches and S_T = steel thickness in inches). When that formula was applied to charges of paste and C-4 explosives, though, charge thicknesses of less than 1/2 inch were seldom used because misfires were thought more likely to occur with thinner charges of those relatively insensitive explosives; this safety rule was not applied to the more sensitive EL506A-5 Detasheet explosive. Although specifications of actual test charges and complete dimensions of steel beams are listed in Appendix C, they are summarized in Table VI.



(a) K3174



(b) K3224

Fig. 20. Wide-flange steel beams used for explosive-cutting tests; (a) 36WF300 and (b) 14WF426.

Table VI. Details of Steel Test Beams and Experimental Explosive Charges

Wide-Flange Steel Beam				Calculated Explosive Charge			Actual Charge Used					
							Maximum[c]			Minimum[d]		
Type	Flange Thickness (in.)	Web Thickness (in.)	Cross-Sectional Area (sq in.)	Army Formula $P = \frac{3/8\ A}{1.34}$ (lb)[a]	SRI Formula $C_T = 1/2\ S_T + 1/8$, $C_W = 4\ C_T$ (in.)[b]	Modified Formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ (in.)	Thickness (in.)	Width (in.)	Weight (lb)	Thickness (in.)	Width (in.)	Weight (lb)
16WF50	5/8	3/8	14.70	4.11	F-7/16x1-3/4 W-5/16x1 1/4	F-5/16x15/16 W-3/16x9/16	F-5/8 W-5/8	2-1/4 1-3/4	1.37	F-3/8 W-9/32	3/4 3/4	0.56
10WF49	9/16	3/8	14.40	4.03	F-13/32x1-5/8 W-5/16x1-1/4	F-9/32x27/32 W-3/16x9/16	F-9/16 W-9/16	1-1/4 1-1/4	1.37	F-1/2 W-1/2	1 1	1 01
14WF74	13/16	7/16	21.76	6.09	F-17/32x2-1/8 W-11/32x1-3/8	F-13/32x1-7/32 W-7/32x21/32	F-17/32 W-11/32	2-1/8 1-3/8	2	F-3/8 W-11/32	2-1/8 1-3/8	1 46
24WF76	11/16	7/16	22.37	6 26	F-15/32x1-7/8 W-11/32x1-3/8	F-11/32x1-1/32 W-7/32x21/32	F-9/16 W-3/8	1-7/8 1-3/8	1.76	F-1/2 W-11/32	1-1/2 1-3/8	1.26
36WF300	1-11/16	15/16	88.17	24.67	F-31/32x3-7/8 W-19/32x2-3/8	F-27/32x2-17/32 W-15/32x1-13/32	F-1 W-11/16	3 2	7.73	F-3/4 W-1/2	2 1-1/2	4.25
14WF426	3-1/16	1-7/8	125.25	35.05	F-1-21/32x6-3/4 W-1-1/16x4-1/4	F-1-17/32x4-19/32 W-15/16x2-13/16	F-1-3/4 W-1-1/4	4-1/2 3-1/8	13.27	F-1-1/2 W-1	4 3	11.75

(a) P = pounds of C-4 explosive, A = cross-sectional area of member in square inches, and 1 34 is relative effectiveness factor for C-4 explosive in relation to TNT as unity.

(b) C_T is charge thickness and S_T is steel thickness, both in inches, "F" and "W" signify the thicknesses and widths in that order of the flange and web charges.

(c) Maximum size charge that completely cut the beam.

(d) Minimum size charge that completely cut the beam.

(3) Charge Placement and Priming Methods. To establish reliable techniques for explosive demolition of irregularly shaped structural steel members, five charge placements and priming methods were investigated in the explosive cutting of wide-flange steel beams. Single explosive charges detonated on one side cannot completely cut structural steel beams with their wide flanges and H-shaped configurations. To sever such beams, separately primed multiple charges must be simultaneously exploded against the web and across the four half flanges formed by the connection of the web to the top and bottom flanges. Simultaneous detonation of individually primed multiple charges separated only slightly from each other requires precise initiation of the charges by accurately positioned detonators. Because explosive shock travels through steel at up to 19,000 feet per second, the shock wave from a premature detonation of one charge will displace the other charges so that the steel beam will not be cut (10). Hence, optimization of techniques for successful explosive cutting of wide-flange steel beams necessitated the evaluation of five charge placements and priming procedures. The five charge placement and priming procedures are designated methods "a" through "e" to coincide with their lettered footnote descriptions in Appendix C.

In method "a" as recommended by SRI, a continuous strip of explosive was placed directly against the two half flanges and web on one side of the beam so that it formed a C-shaped charge. A U. S. Army special electric blasting cap primed the C-shaped charge at the center and not at the end as specified by SRI (7). To cut the other two half flanges, two explosive charges placed one on each half of the upper and lower flanges were offset 1 inch from the flange portions of the C-shaped charge. These two half-flange charges were end-primed with U. S. Army special electric caps. Connected into a series firing circuit, the three blasting caps detonated the three separated charges when initiated by current from a blasting machine (Fig. 21).

Priming method "b" used the same basic charge placement and points of charge initiation as the first method, but less offset was used between the two half-flange charges on one side of the beam and the continuous charge on the other side, and a detonating cord firing system was used to achieve simultaneous initiation of the three separately primed charges. On beams with flange thicknesses of less than 2 inches, the two half-flange charges were offset so that one edge was opposite the center of the flange portions of the continuous C-shaped charge on the other side of the beam; on beams having

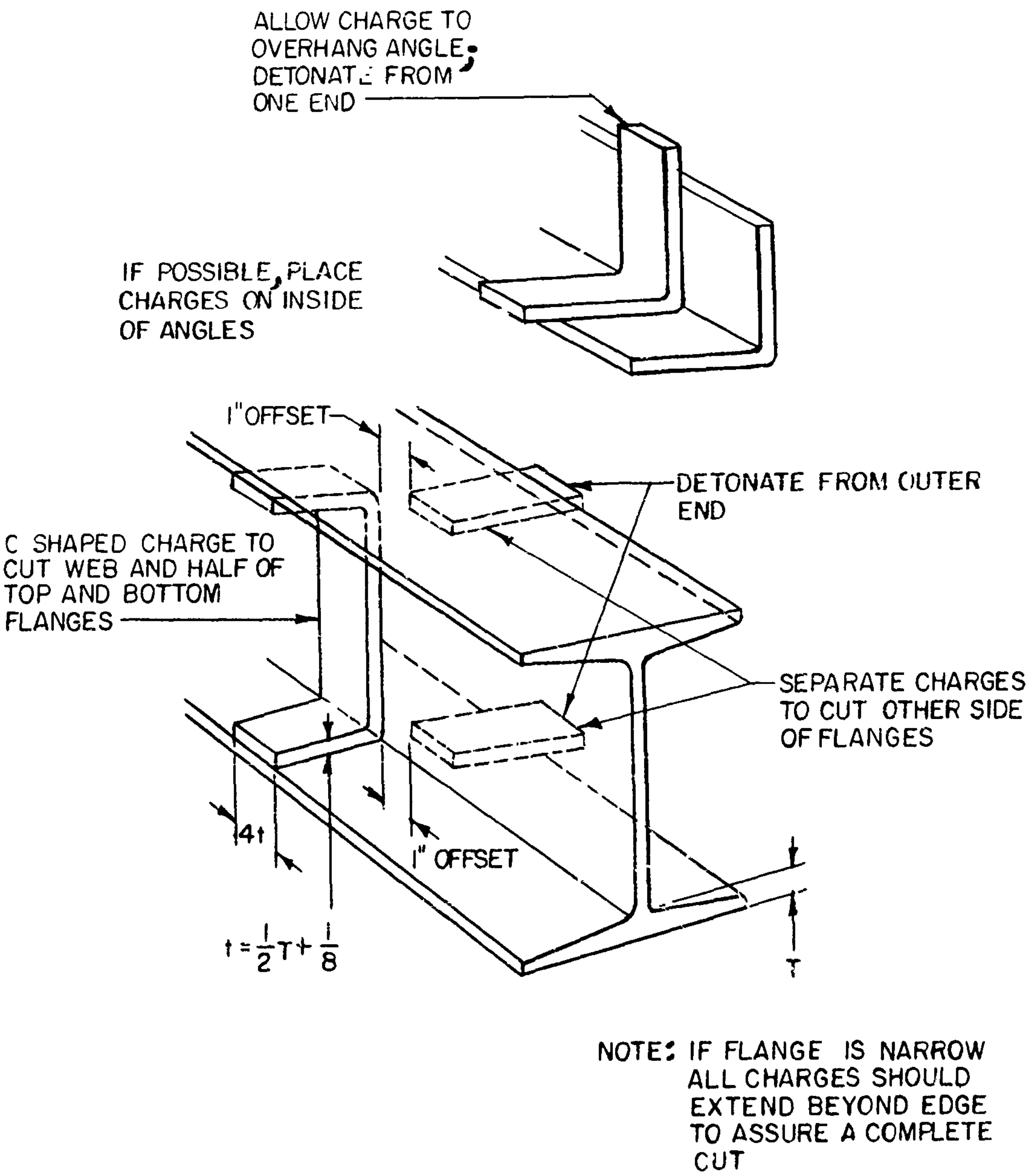
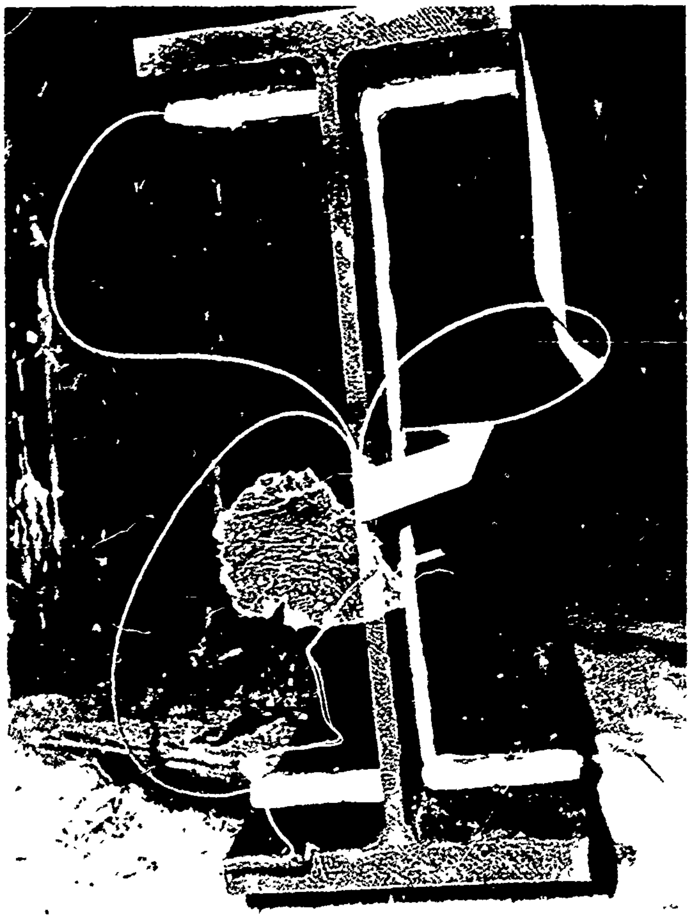


Fig. 21. Charge placement and priming technique recommended by SRI for explosive cutting of steel beams.

flange thicknesses of 2 inches or greater, the two half-flange charges were offset so that one edge was opposite an edge of the flange portions of the continuous charge on the other side of the beam. Three equal lengths of detonating cord, each of which had either a J-1 non-electric cap or an overhand knot (in a 10-inch bight) at one end, primed the center of the one continuous charge on one side of the beam and the ends of the two flange charges on the opposite sides. Fastened to the other ends of the three lengths of detonating cord, a J-2 electric blasting cap exploded the detonating cord priming assembly which, in turn, simultaneously detonated the three separated explosive charges (Fig. 22).



K3218

Fig. 22. Detonating cord firing system used for priming and simultaneous explosion of continuous and half-flange charges on steel beams.

In method "c", a continuous charge of explosive on the two half flanges and web of one side of the beam and two half-flange charges on the opposite side again comprised the charge placement technique; however, electric blasting caps in a simple series circuit primed the ends of all three charges and formed the firing system. As with the two previously described charge placements, a strip of explosive was continuous across the upper and lower flanges and the web, and two separate charges were on the upper and lower flanges only on the other side of the beam. Either a J-2 or T-6 electric blasting cap (test model of M6 cap) primed and detonated the ends of the three separated charges. The three caps were connected in a series circuit and were initiated by current from a blasting machine.

In method "d", two strips of explosive continuous across the two half flanges and webs on both sides of the beam were used, with an offset between the charges. The explosive was formed into a rectangular charge that was continuous across the bottom surface of half of the upper flange, down the entire depth of the web, and across the top surface of half of the lower flange, forming a linear charge that bisected one side of the beam. A similar charge of equal explosive content was placed on the opposite sides of the beam with a 1-inch longitudinal offset between the two charges. A T-6 electric blasting cap primed the center of each of the two continuous charges; inserted into the explosive at its center point on the web, the two caps formed a simple series electrical firing system for simultaneous initiation of the separately primed charges. A current U. S. Army charge placement method was recommended for priming and detonation from the outer ends of the two continuous charges (Fig. 23); this technique required priming at only two points, but used considerably more explosive than the three charge techniques that employed three points of initiation (3). Of greater importance. though, detonation of the two separate continuous charges from outer ends, as recommended by the U. S. Army, had previously failed to produce simultaneous detonation in the linear charges, so steel beams were not completely cut during the preliminary evaluation of paste explosive for general demolition use (16). Thus, after end priming had also failed to effect simultaneous detonation of the three charge techniques of explosive placement (test shots 34 and 35, Appendix C), only center priming and initiation of the dual continuous charges emplaced at a 1-inch offset on both sides of the beams were evaluated.

The same charge placement and points of charge initiation were used for the method "e" demolition technique under

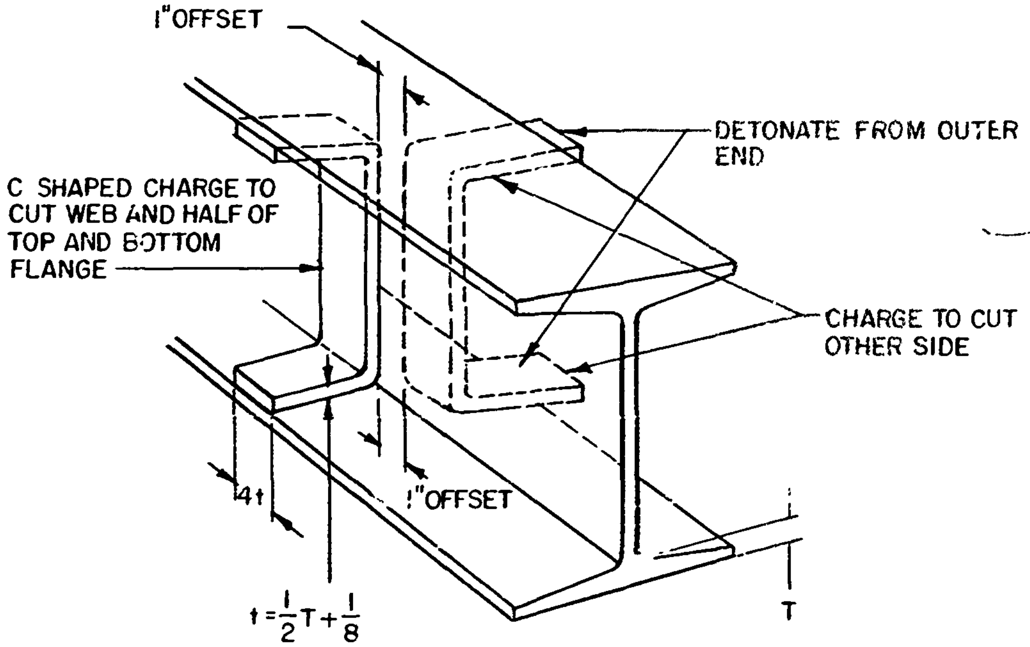
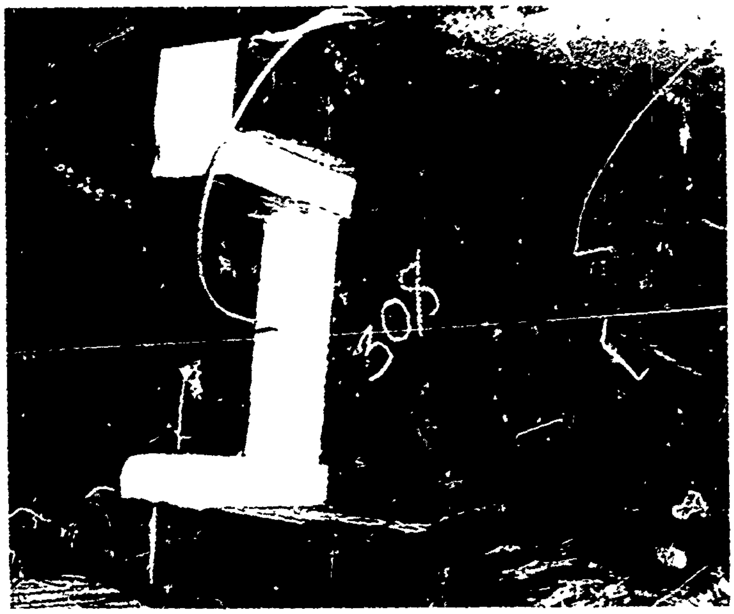
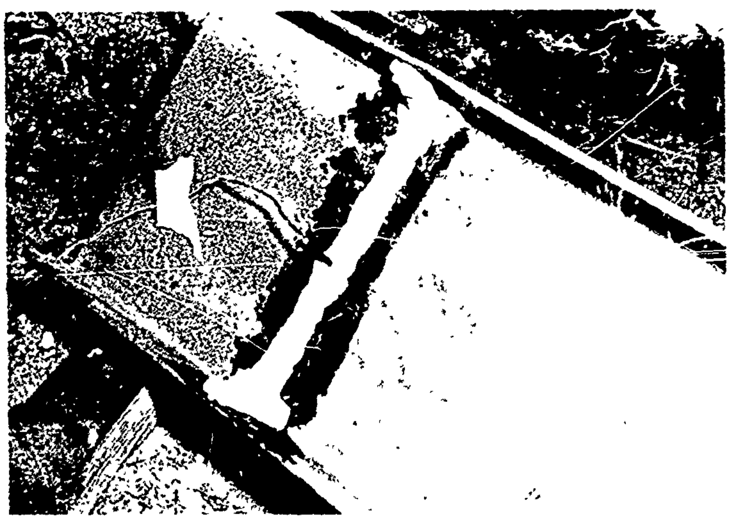


Fig. 23. U. S. Army charge placement method evaluated for cutting steel beams with explosive charges detonated at center.

which a detonating cord firing system for simultaneous explosion of the two separately primed continuous charges to cut steel beams was evaluated. A detonating cord priming assembly, which consists of two equal lengths of detonating cord with either an overhand knot tied in a bight at one end or with a J-1 nonelectric cap crimped to an end, primed and initiated the center of the continuous C-shaped explosive charges. The overhand knots or the nonelectric blasting caps were embedded into the explosive at the center of the web portions of the charges. Fastened to the opposite ends of the two lengths of detonating cord, a J-2 or M-6 electric blasting cap detonated the priming assembly which, in turn, exploded the continuous charges. Figure 24 shows the center priming of a continuous explosive charge on one side of a beam with one half of a detonating cord priming assembly; similar priming with a J-2 electric blasting cap of a similar charge is also shown.



(a) 3244



(b) K3256

Fig. 24. Priming of continuous explosive charges for simultaneous detonation by detonating cord priming assembly which shows (a) detonating cord lead with nonelectric cap in explosive; and (b) by electric blasting caps. (Note: Both figures show only one side; charge placement and priming were similar on other side.)

(4) Methods of Placing and Securing Charges. For maximum destructive effect, steel-cutting explosive charges must be placed and secured so that the entire surface areas of the explosive and steel are in intimate contact along the desired line of cut. Complying with this rule is as important as using the optimum explosive weight and placement because even minute air gaps between the explosive and steel will drastically reduce the cutting efficiency of the charge (3)(7). In field operations, troops often use wire and wooden blocks to fasten and secure explosive charges to their targets. By racking wire tightly against wooden blocks so that they press the explosive tightly against target surfaces, explosive charges can be fastened and held securely for indefinite periods of time. However, this experimental program did not include the evaluation of methods of securing explosive charges to steel members, so less permanent means were used to secure the test charges to the steel beams.

Hand-placement and extrusion methods were both used to place explosives on the beams, and automotive water pump grease, masking tape, and wooden blocks were utilized to secure the charges to the steel surfaces. Charges were emplaced on steel beams, both old and new, rusty and nonrusty, painted and unpainted, the explosive contact surface of the beam being coated either with grease or plain steel. Precut to the specified widths, thicknesses, or both, C-4 and EL506A-5 explosive charges were simply placed tightly against the steel surface of the beams along the desired line of rupture, and if grease was not being used, were taped or blocked securely in place; taping or blocking often was not necessary on grease-coated steel surfaces although it would have been necessary in field operations if the charges were not to be detonated immediately. A modified commercial caulking gun extruded columns of paste explosive, 5/8 inch in diameter, on to the steel beams in the specified charge weights and configurations. A satisfactory method for placing paste explosive charges, this extrusion technique was nevertheless cumbersome and time consuming, so the faster and simpler hand-placement method replaced it. Hand placement of paste explosive involved only the pressing of the explosive on to the steel beam in the correct charge configuration along the desired line of cut; charges were weighed for experimental control and comparison (Fig. 25) although this was not required in field operations.

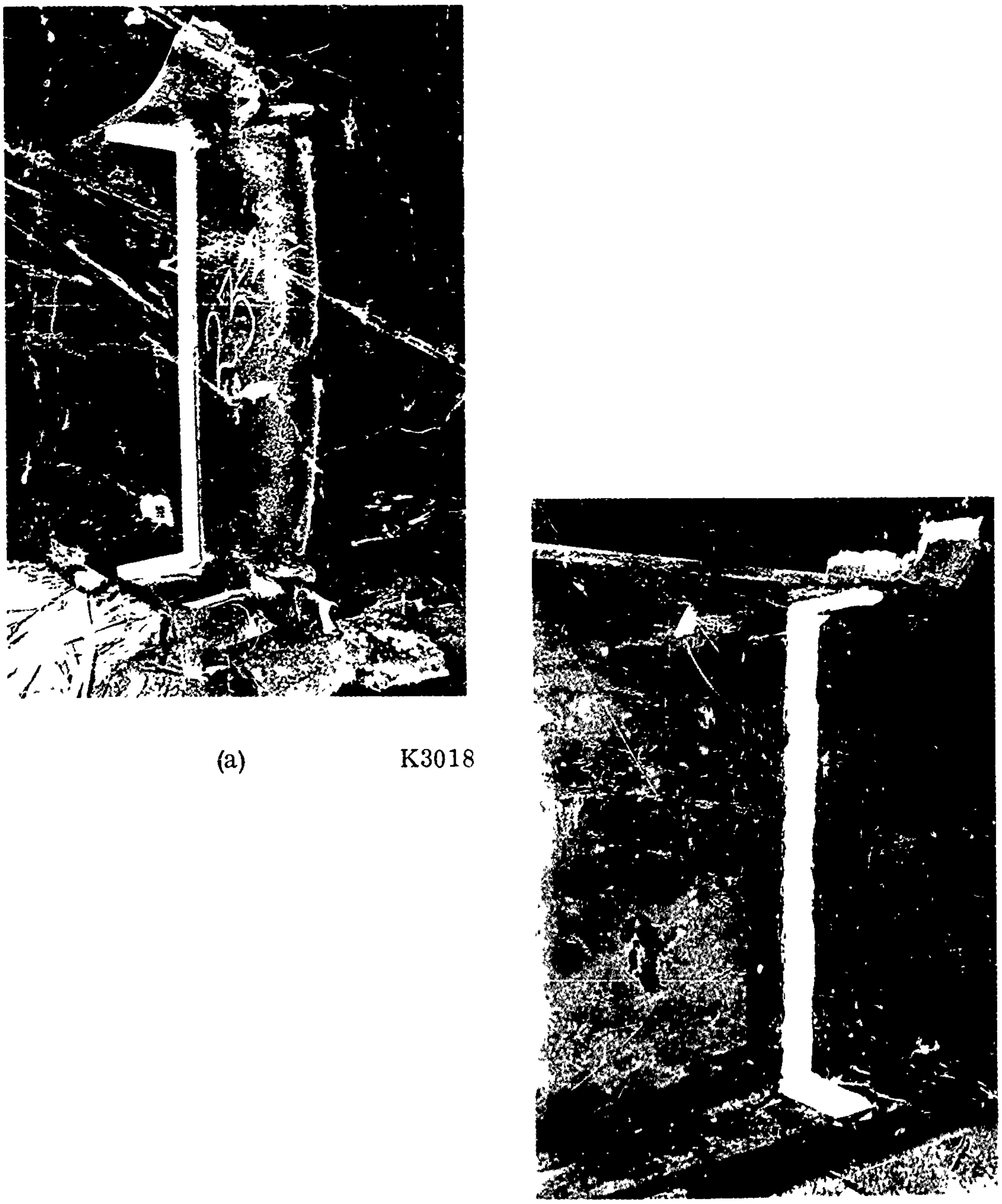
Paste explosive charges adhered well to plain steel surfaces, either rusty or nonrusty, but on grease-coated steel, the paste explosive adhered so much better that it was difficult to pull the

K3198

Fig. 25. Hand placement of paste explosive on to grease-coated steel beam.

explosive off. Complete removal of all paste explosive in a charge on grease-coated steel required the use of a knife or spatula. Composition C-4 and EL506A-5 Detasheet explosives both adhered well to steel surfaces covered with a thin coat of grease and not so well on steel with a thick coat of grease. Neither of those explosives adhered to grease-coated steel as well as paste explosive, but the C-4 explosive with its characteristic tacky surface adhered better than did the Detasheet explosive (Figs. 26 and 27).

(5) Test Results. Experimental results for the 106 explosive-cutting tests on wide-flange beams are described in Appendix C. As shown therein, of the 106 experimental charges, 69 were of paste explosive which was being evaluated for the first time for steel cutting, 30 were Composition C-4 explosive which was used for



(a) K3018

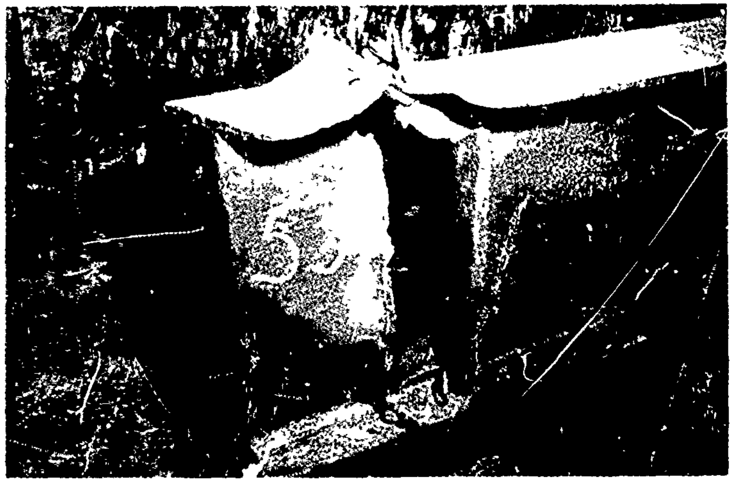
(b) K3006

Fig. 26. Experimental charges of (a) Composition C-4 and (b) paste explosives held on 24WF76 steel beams by grease. (Charges were also on opposite side, upper and lower flanges.)

Fig. 27. EL506A-5 Detasheet explosive charge emplaced on grease-coated surface of 24WF76 steel beam.

controlled comparison with the other two explosives, and seven were EL506A-5 Detasheet explosive which was available in limited quantity for initial evaluation. Seventy-nine out of the 106 explosive charges completely cut the beams, and of the 27 experimental charges that failed to cut the beams, 20 were paste explosive, four were Composition C-4 explosive, and three were EL506A-5 Detasheet flexible explosive. Actual explosive expenditures for successful cutting of the beams ranged from 1/5 to 3/8 of the calculated amounts for paste explosive, 1/6 to 3/8 for Composition C-4 explosive, and 1/5 to 1/3 for EL506A-5 Detasheet explosive. Those fractions represent the actual amounts used in comparison with the amounts computed by the U. S. Army steel-cutting formula, $P = \frac{3/8\ A}{1.34}$; they are not given for comparison of the relative steel-cutting effectiveness of the three test explosives.

K3238



J6404

K3258

Fig. 28. Typical incomplete explosive cuts on wide-flange steel beams. (Fig. 24 shows the charge setup for test shot 312 and a similar setup for test shot 306.)

Four defects in charge placement, priming, and initiation caused the 27 failures of explosive charges to cut the wide-flange steel beams (Fig. 28). Lack of simultaneous detonation between the charges emplaced at offset distances on opposite sides of the beams produced 18 demolition failures; 16 occurred with electric cap priming and two with detonating cord priming. Uncut half flanges on one side of the beams and explosive splattered on the wall of the steel pit verified that simultaneous detonation had not occurred in the multiple charges individually primed and located at separated points on the wide-flange steel beams. Low-density C-4 explosive also contributed one failure to cut a steel beam (test shot 302), explosive charges that were too thin yielded six incomplete cuts, and the other two failures were caused by excessive offset between half-flange and continuous charges on opposite sides of the beams so that the beam fillets were not cut. Causes and effects of the demolition failures and the techniques used to eliminate them are discussed in more detail in the analyses of test results.

As is so with explosive charges detonated in contact with steel plates, contact charges of high explosive produced steel failures on wide-flange beams through the combined destructive effects of spall and tensile fracture. Spall damage occurred on the free surface of the steel opposite the charge explosion. Tensile fracture propagated from the spall side of the steel, cracking through to the charge side of the steel and formed a longitudinal split down the center of the depression where the charges exploded and compressed the steel. Although spall damage contributed to the overall severing of the beams, the longitudinal split or tensile fracture was the main destructive effect that severed wide-flange steel beams (Fig. 29). Lengths of the longitudinal splits equalled the lengths of the charges (Fig. 30).

Because longitudinal splits formed in the steel under the center of the linear half-flange charges as well as under the continuous charges on the opposite sides of the beams, the half-flange charges had to be offset just enough from the continuous charges for the splits from the offset charges to intersect each other, or the fillets of the beams were not cut. The 1-inch offset recommended both by the U. S. Army and SRI was often too much. The optimum offset for charges placed and simultaneously exploded on both sides of the beam was established as center of one charge aligned opposite an edge of the other charge on steel thicknesses of less than 2 inches. On steel thicknesses of 2 inches and over, the opposing charges were

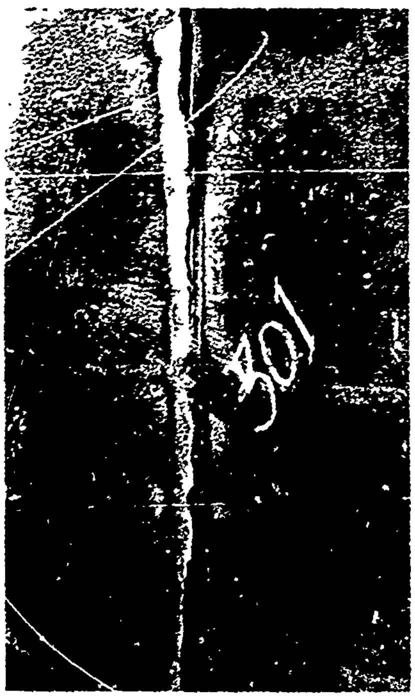
K3021

Fig. 29. Wide-flange steel beams severed by contact explosive charges. (Figure 26 shows charge setup.)

offset so that the edge of one charge was aligned along an edge of the other. With less offsets, the charges were diametrically opposed and consequently without free reflection surfaces so that spall could not form; hence, they compressed the intervening steel and tended to neutralize the destructive force of each (Fig. 31). The tolerance required for intersection of the longitudinal splits formed under the half charges was not as critical with the two continuous charges offset and detonated on opposite sides of the beams. The explosion of these two slightly offset charges from both sides tended to shear the beams apart through the combined effects of two longitudinal splits instead of one.

An explosive charge continuous across the half flanges and web on one side of beams and two half-flange charges offset slightly on the other side completely cut wide-flange steel beams when the charges had width-to-thickness ratios of about 2:1 to 4:1 as

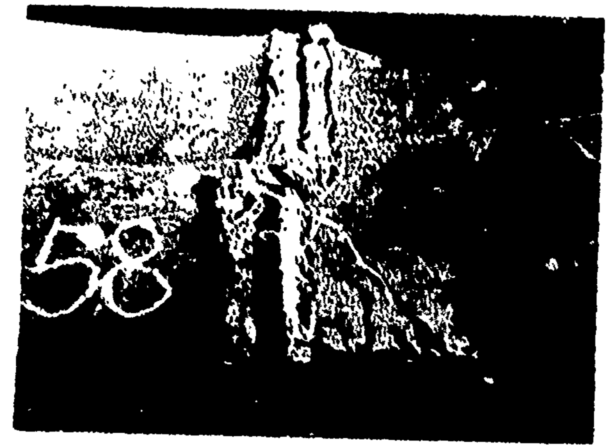
(a) K3192



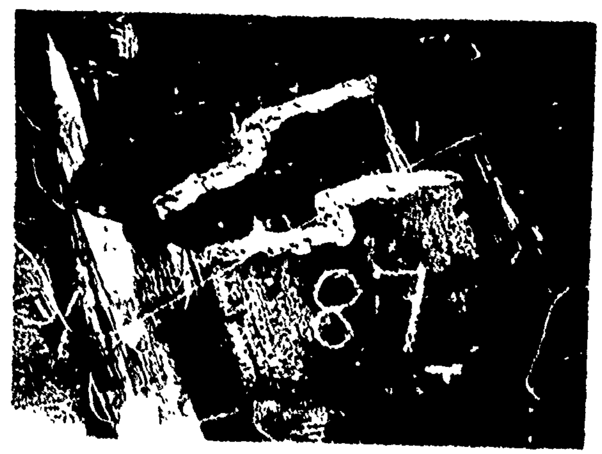
(b) K3205 (c) K3184

Fig. 30. Longitudinal splits (tensile fractures) formed on steel beams by contact explosive charges. Incomplete splits appeared in (a) and (b), and beam was severed by complete split in (c). Note that split has not broken through charge side of steel in (a).

(a) K1608



(b) J6311



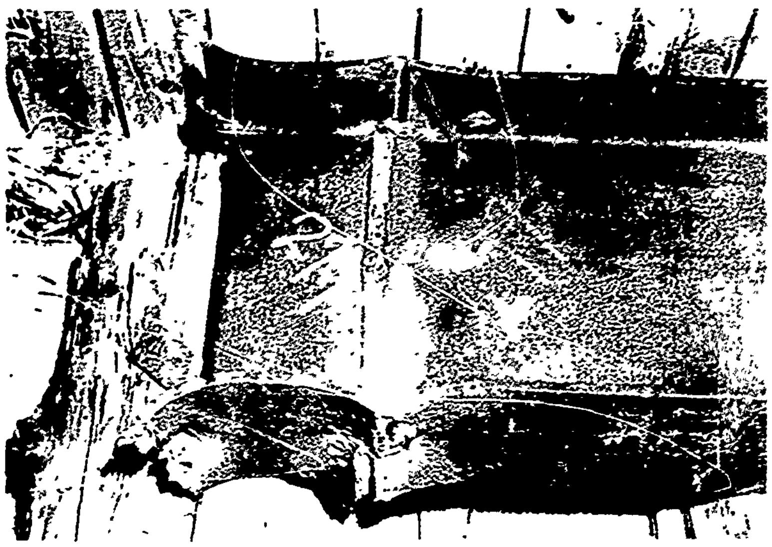
(c) J6308

Fig. 31. Criticality of offset between explosive charges placed to cut wide-flange steel beams from both sides. (a) and (b) Excess offset produced incomplete cuts; and (c) optimum offset yielded complete cut.

J6320

Fig. 32. Excessive destructive effect produced on wide-flange steel beams by explosive charges with thicknesses and widths exceeding the optimum.

determined by the steel thickness involved. Because those ratios bracketed the optimum, thicker and wider charges caused significantly more destructive effect than is required for explosive demolition of steel beams (Fig. 32). Thinner and narrower charges either only spalled the free surface steel without forming a longitudinal split or spalled the steel and partially split the beam with the longitudinal tensile fracture. A phenomenon common to steel cutting with contact charges of high explosives, spalling of the steel on the free surface occurred prior to and apparently independently of the formation of the longitudinal tensile fracture because spall was the only damaging effect of thin charges. Conversely, tensile fracturing of the steel did not occur independently of spalling. Tensile fractures in the form of the characteristic longitudinal split were frequently visible on the spalled side but not visible on the charge side of the steel (Fig. 33). Moreover, when emplaced as continuous strips of explosive across one side of a beam, C-shaped charges detonated at the center produced cross fractures in the outer edges of the flanges at both ends of the charges; that cross-fracture effect is visible in the top photograph of Fig. 28.



K3127

Fig. 33. Spall damage without tensile fracture inflicted on web of steel beam by excessively thin explosive charge.

c. Experiments on Steel Channels. Fifteen test firings were performed to evaluate paste, Composition C-4, and EL506A-5 explosives for demolition of 15 by 3-3/8 American standard steel channels each with a cross-sectional area of 14.64 square inches. During this test phase, seven paste explosive charges, and four charges each of Composition C-4 and EL506A-5 Detasheet explosives were evaluated.

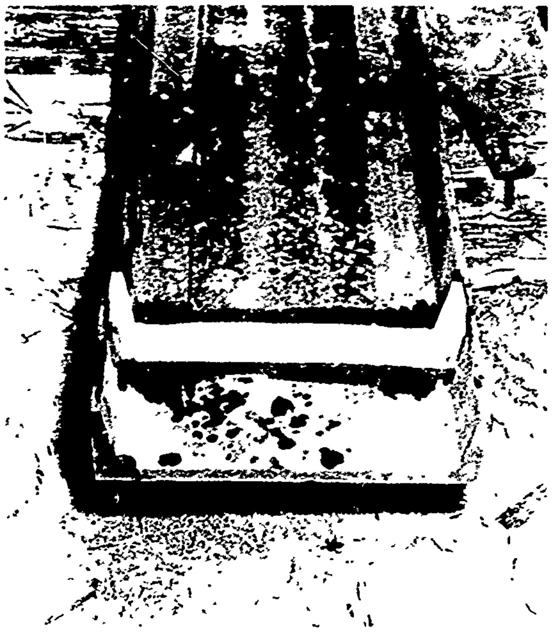
(1) Test Procedures. The formula $C_T = 3/4\ S_T$, $C_W = 3\ C_T$, a further modification of the SRI formula (where C_T and S_T = charge thickness and steel thickness in inches, respectively, and C_W = charge width in inches), was used as a guide to compute the dimensions of the experimental charges. Because the steel channel had a flange thickness of 5/8 inch and a web thickness of 3/4 inch, application of the formula just given prescribed two flange charges of 15/32-inch thickness by 1-13/32-inch width connected by a web charge of 9/16-inch thickness by 1-11/16-inch width. Continuous charges of about those dimensions (except for EL506A-5 Detasheet charges which were about 3/8 inch thick, the thickness of two layers of the sheet explosive) were placed in contact with the steel across the half flanges and web. U. S. Army special electric blasting caps, J-2, primed

and detonated all of the charges at their center point on the channel web (Fig. 34).

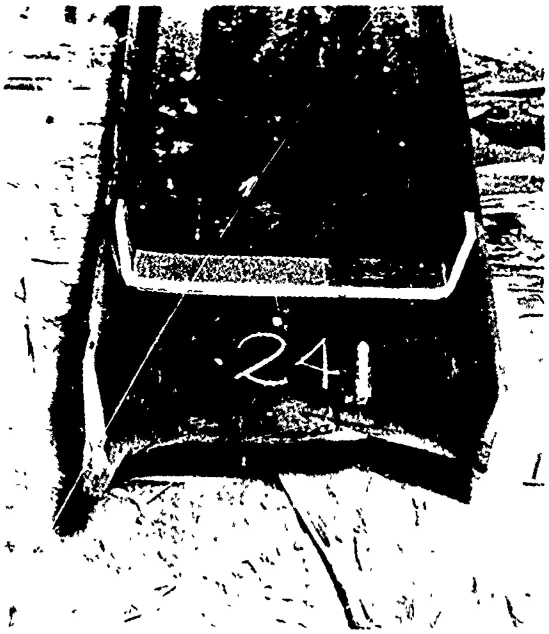
(2) Test Results. All 15 charges of the three kinds of explosives, which contained only 18.68 to 21.36 percent of the explosive quantity prescribed for use by the steel-cutting formula $P = \frac{3/8\ A}{1.34}$, completely cut the steel channels. Explosive weights used in the minimum size charges represented a relationship to the steel cross-sectional area of but 5 to 6 percent, or pounds of explosive equal about 1/19 to 1/16 (maximum) of the cross-sectional area, yet lesser explosive weights would have severed the steel channels. Explosive charges calculated by the SRI formula would have produced successful explosive cuts of the steel member, based on previous test results. Results of these tests, therefore, again reveal the significant effect of optimum charge thicknesses and widths on the steel-cutting ability of high-explosive charges (Fig. 35). Details of experimental charges and test results are listed in Appendix C as test shots 239 to 251b.

9. Explosive-Cutting Tests on Wire Rope. Paste and Composition C-4 explosives were used to evaluate two demolition techniques for cutting wire ropes of improved plow steel, 1 and 1-1/2 inches in diameter. The 1 inch in diameter, wire rope had six strands of 19 wires per strand or a total of 114 improved plow-steel wires. The wire rope, 1-1/2 inches in diameter, had seven strands of seven wires each or a total of 49 steel wires. Because of its high strength, flexibility, resiliency, spiral construction, irregular shape, and small cross-sectional area, wire rope has great resistance to demolition by explosive shock from contact charges, especially when unstressed as the wire ropes were in these experiments. Successful explosive cutting requires intimate contact between the surface of the steel wires and a high explosive that has great shattering power. Both C-4 and paste explosives with their moldable characteristic were considered excellent explosives for cutting wire rope. But EL506A-5 Detasheet explosive, although flexible, was considered significantly less adaptable because its smooth, tough surface did not complement the achievement of intimate contact between the explosive and the wire rope. Hence, this explosive was not evaluated in this phase.

a. Test Procedure. Both single-charge and dual-charge techniques for explosive demolition of wire rope were investigated in 25 test firings. The formula $P = \frac{D^2}{1.34}$, prescribed by the U. S. Army for

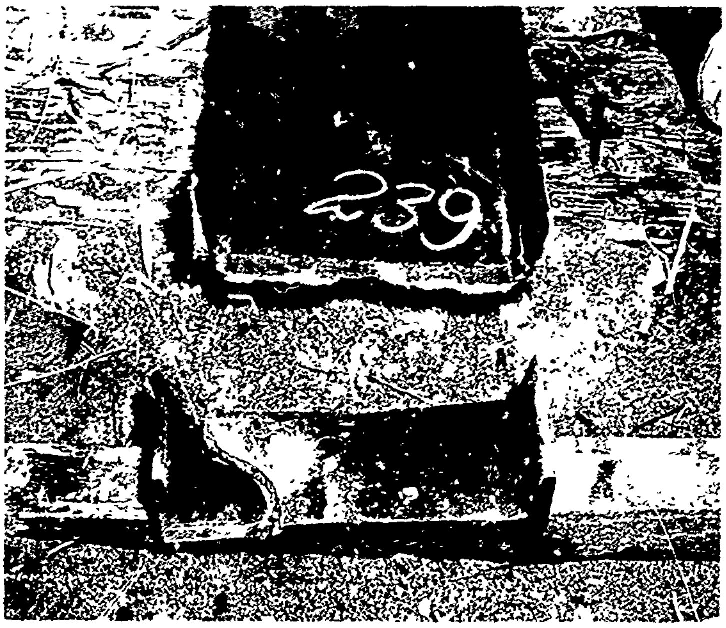


K3046 (a)

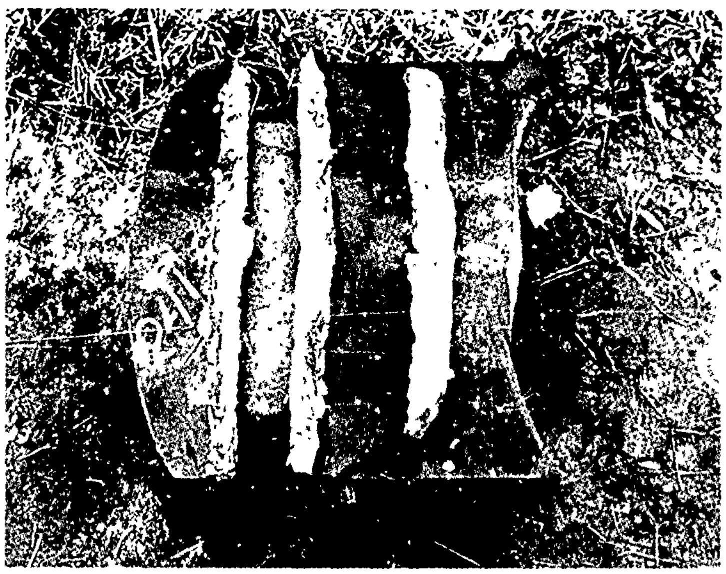


(b) K3050

Fig. 34. Contact charges of (a) Composition C-4 and (b) EL506A-5 Detasheet explosives emplaced on 15 by 3-3/8 steel channels.



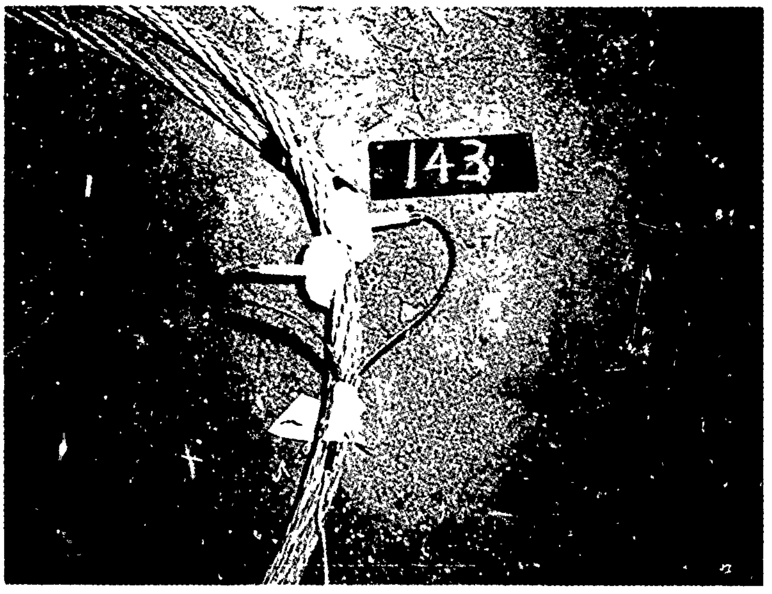
(a) K3047



(b) K3052

Fig. 35. Typical explosive cuts on 15 by 3-3/8 steel channels; (a) Charge side of test shot 239 and (b) spall side of test shot 241.

calculation of charges to cut rods and cables of small diameters (3), was used as a guide for computation of the explosive charges and for comparative analysis of actual charges to calculated ones. Single-explosive charges were pressed tightly into contact with the wire rope along one side and detonated at the charge center with either a J-2 or M6 electric blasting cap. Dual-explosive charges were offset on opposite sides of the wire rope with a 1-inch overlap between the two charges that were in close contact with the steel wires. A detonating cord priming assembly, which consisted of two equal lengths of detonating cord with J-1 nonelectric caps crimped to one end and with a taped J-2 electric cap connecting the other ends, simultaneously detonated the two offset charges so that they would shear the wire rope (Fig. 36). Six single-charge and 19 dual-charge experiments comprised this phase of the test program.



J3974

Fig. 36. Dual charges of paste explosive (2/3-pound total weight) primed for simultaneous detonation to shear wire rope, 1-1/2 inches in diameter.

b. Test Results. As shown in the summary of explosive-cutting test results on wire rope in Appendix C, which also gives the details of the charges and the tests, results of the experimental firings reveal 9 out of the 19 dual-explosive charges completely cut the wire ropes of both 1- and 1-1/2-inch diameters; these successful cuts were achieved with charges containing about 34 to 72 percent of the explosive calculated by the U. S. Army steel-cutting formula. Eight of the ten dual-explosive charges cut all but 1 to 3 wires of the steel ropes; this effect destroyed their usefulness. However, like the other explosive experiments, the wire rope was not considered completely cut unless severed. Comparison of the two explosive demolition techniques, single charge versus dual charges, showed that only one single charge out of six completely severed the wire ropes; two other charges cut all but one wire, but these charges used 65 to 72 percent of the calculated amount of explosives. Based on these limited tests, explosive cutting with dual-explosive charges, simultaneously detonated from opposite sides, is considered a more reliable technique for demolition of wire rope than is cutting with single explosive charges detonated along one side (Fig. 37).

J3973

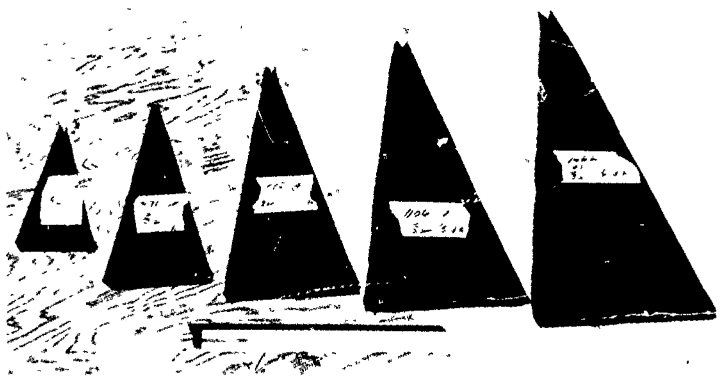
Fig. 37. Improved plow-steel wire rope, 1-1/2 inches in diameter, severed by dual-explosive charges detonated simultaneously.

10. Explosive-Cutting Tests on Steel Bars. During 155 explosive-cutting tests, the cross-fracture, the saddle charge and diamond charge techniques of cutting round and square steel bars with high explosives were evaluated; for comparison, dual charges offset on opposite sides of bars were investigated in nine test shots. In subsequent paragraphs, the test procedures peculiar to each explosive-cutting technique are described, but

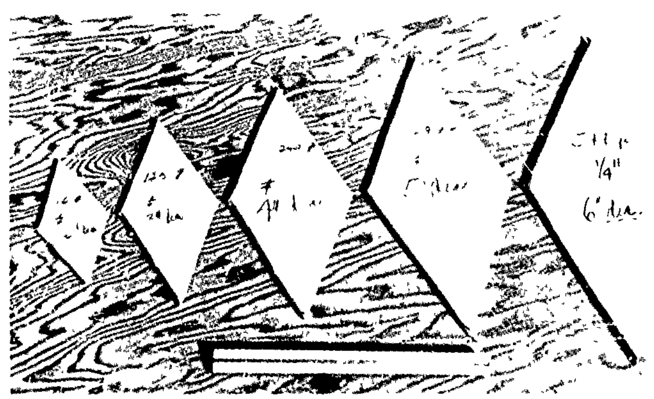
general procedures that apply to all are given in the following two paragraphs.

a. General Test Procedures. These explosive-cutting experiments were performed on 2- and 4-inch square steel bars and 2-, 3-, 4-, and 6-inch diameter round steel bars of both mild and alloy steel; hence, calculation of the charges involved the application of two current U. S. Army steel-cutting formulas in addition to specialized formulas. The U. S. Army formulas used for comparison of calculated explosive weights to actual explosive weights of the experimental charges were $P = \frac{3/8\ A}{1.34}$ and $P = \frac{D^2}{1.34}$. The formula $P = \frac{3/8\ A}{1.34}$ is prescribed for calculation of charges to cut round steel bars with diameters exceeding 2 inches, and the $P = \frac{D^2}{1.34}$ formula is specified for computation of explosive charges to cut round steel bars with diameters of 2 inches or less. Charges calculated by those formulas are listed in Appendix C for each of the three demolition techniques evaluated and which are described here.

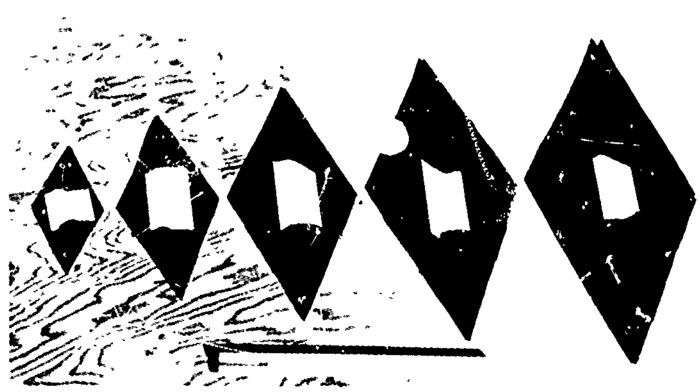
Charges of C-4 and EL506A-5 explosives were prefabricated to the specified dimensions before they were emplaced on the steel bars, but the semifluid paste explosive, which was not adaptable to prefabrication, was either extruded or hand placed on the steel specimens in the correct configuration. Composition C-4 explosive was used to evaluate all three techniques for explosive cutting of steel bars, but paste explosive was employed for evaluation of the cross-fracture technique only, and EL506A-5 Detasheet explosive, available in limited quantities, was evaluated only with the diamond charge technique. Blocks of C-4 explosive, 2 by 2 by 10-3/4 inches in dimensions, were sliced longitudinally into the specified charge thicknesses. These slices of C-4 explosive were then either placed directly on the square steel bars in the correct charge dimensions, or butted together to form rectangles of explosive for prefabrication of charges to cut round steel bars. In prefabrication, a cardboard pattern like a triangle (for saddle charges) a diamond, or rectangle (for cross-fracture charges) was laid on the explosive which was cut to the pattern of the cardboard. The cardboard pattern and the shaped explosive were then taped into a prepackaged charge. For emplacement, the cardboard pattern was simply removed from the explosive before the preshaped charge was placed on or around the steel target. EL506A-5 Detasheet explosive required only precutting to the specified shapes provided by the cardboard patterns. Preshaped sheets of EL506A-5 explosive were stacked vertically to form charges of thicknesses exceeding that of a single sheet (Fig. 38).



(a) K1587



(b) K1584



(c) K1586

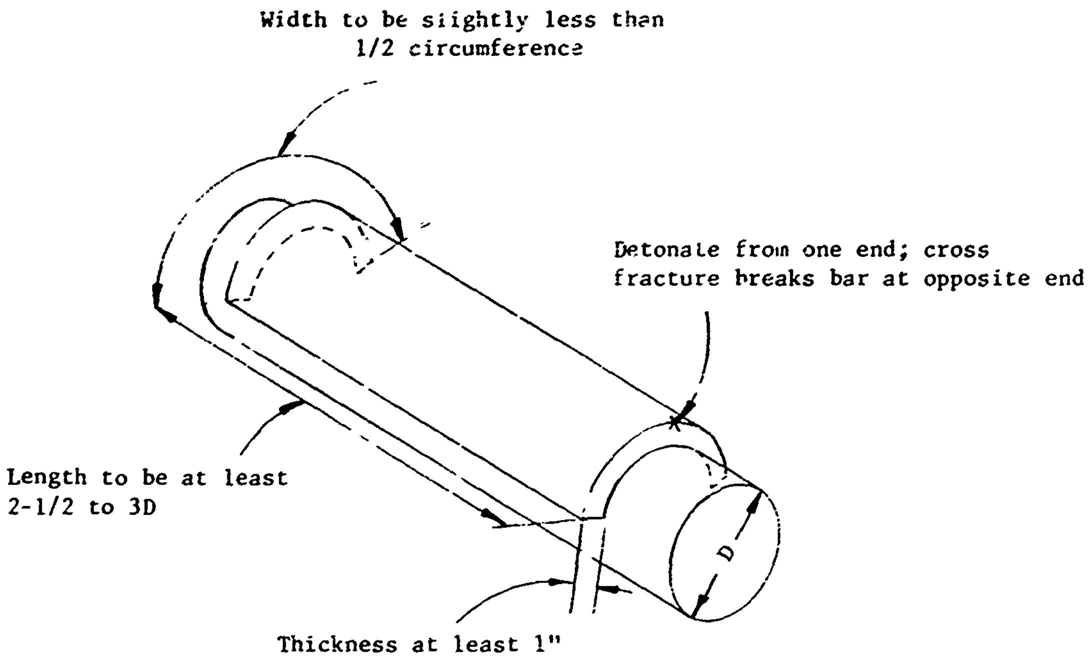
Fig. 38. Explosive charges prefabricated for cutting round steel bars. (a) C-4 saddle charges; (b) C-4 diamond-shaped charges; and (c) diamond-shaped charges of EL506A-5 Detasheet explosive.

b. Steel-Cutting Experiments with Cross-Fracture Explosive Technique. The cross-fracture explosive demolition technique was evaluated in 83 test shots, as follows:

(1) Procedure. The cross-fracture explosive technique for cutting steel bars (round, square, or rectangular) utilized the destructive effect of the end split or cross fracture formed in steel at the end of a charge opposite the end where detonation was initiated. An end split or cross fracture is one of the four observable effects of detonating a high-explosive charge in contact with a steel plate. The other three effects are the indentation or depression in the charge side of the plate, the spall from the free surface or back side of the plate, and the longitudinal split formed in the steel under the entire length of the charge. So far this report has described the use of the destructive effect of the longitudinal split to sever steel plates, angles, wide-flange beams, and channels. Through proper placement and correct point of initiation of optimum size explosive charges, the end split (or cross fracture) was controlled and utilized to cut steel bars with significantly less explosive than that required by present U. S. Army explosive techniques.

An SRI innovation developed under contract with USAERDL (7), that is, the cross-fracture steel-cutting explosive technique, was utilized successfully by USAERDL personnel for underwater cutting of 36 steel shafts during explosive demolition of Ohio River Locks in 1961 (17). In this test program as in the aforementioned ones, rectangular charges of explosive were fabricated, emplaced, and detonated in accordance with the specifications illustrated in Fig. 39. During 83 test firings of paste and C-4 explosive charges, the cross-fracture technique for cutting 2- and 4-inch square steel bars and round steel bars, 2, 3, and 4 inches in diameter, was evaluated. Nine of 83 test firings used dual-offset charges. Specific details of the 83 experiments, the steel bars, and the experimental charges are given in Appendix C for square steel bars and for round ones.

(2) Results. Experimental results of 43 test firings on 2- and 4-inch square steel bars presented in the summary of explosive-cutting test results on square steel bars (Appendix C) showed 24 complete cuts and 19 failures to cut the steel bars. Of the 43 test shots, 37 were evaluated by means of the cross-fracture steel-cutting technique, and the other six employed dual charges which were offset and simultaneously detonated on opposite sides of the steel bars.



Charge Calculation

$P = \frac{2}{3} D$* $P = 0.25D^2$ **

Where

P = lb of C-3, or high density C-4

D = diameter of round bar or thickness of square bar

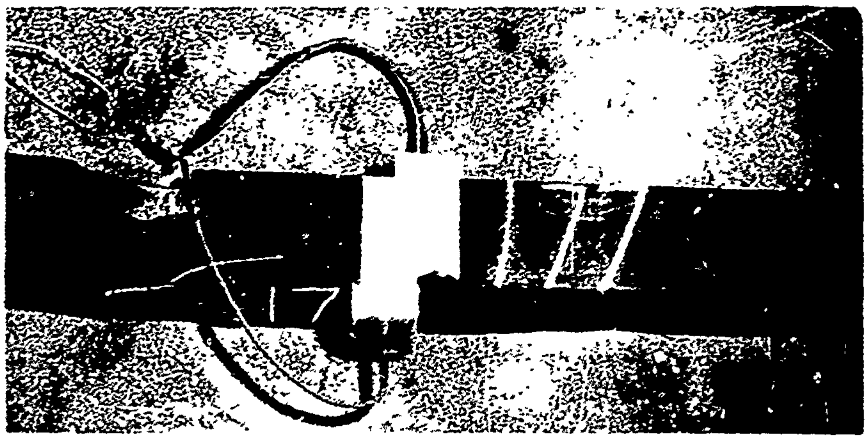
* Bars up to 3" thickness
**Bars over 3" diameter

Fig. 39. Cross-fracture explosive technique for cutting steel bars. (Taken from SRI report (7).)

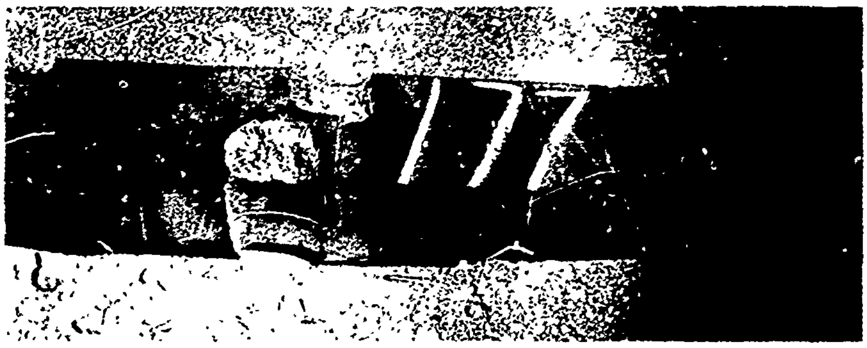
Dual-offset charges, detonated simultaneously by detonating cord priming assemblies, broke the steel bars in three tests with two complete cuts out of four on 4-inch bars and one out of two on 2-inch bars (Fig. 40): complete cuts were achieved with 39 to 75 percent of the explosive prescribed by the U. S. Army steel-cutting formula. The cross-fracture technique yielded slightly better results with 21 complete cuts out of 37 experimental charges detonated on 2- and 4-inch square steel bars. Complete cuts were obtained on 2-inch steel bars with charges containing 49.0 to 86.5 percent of the explosive calculated by the U. S. Army formula. Severing of the 4-inch bars required 24.6 to 50.0 percent of the calculated amount of explosive. Less explosive was needed to break the 4-inch steel bars because the contact area between the explosive and the steel was four times that on the 2-inch bars. The percentages of incomplete cuts were about the same for both C-4 and paste explosives: about 53 percent occurred with C-4 and 57 percent with paste. Because about 98 percent of similar charges completely cut vertical shafts underwater in the Ohio River during 1961, it is thought that the soil contact surface formed by the steel bars lying on the ground may have adversely affected the test results as described in paragraph 7b for steel plates. Undoubtedly, the soil backing interfered with the reflection of the shock wave, and explosive energy was transmitted into the soil (2). To eliminate bias from that source, the steel bars should have been set up so that they had free surfaces opposite the charges, but the effect of this error was not discovered until after this phase of testing had been completed.

With about 1-inch thicknesses, widths equal to the steel widths involved, and lengths equivalent to about 2-1/2 to 3 times the steel thickness, rectangular charges detonated at one end on the 2- and 4-inch square steel bars broke them by a cross fracture extending through and across the steel at the end away from the point of detonation. In many tests, the steel bars were also split by the longitudinal fractures that formed in the steel under the center of the charge, but the cross fractures, not the longitudinal splits, severed the bars. Initiated on the spall side of the steel bar, the cross fractures propagated upward to break through the charge side of the steel and severed the bars at the ends of the charge depression away from the detonation point. Rectangular charges if sufficiently long and detonated at the center broke the steel bars by two cross fractures that formed at each end of the charge (Figs. 41 through 43).

Results of the evaluation of the cross-fracture explosive-cutting technique on round steel bars with diameters of 2,



(a) J6359

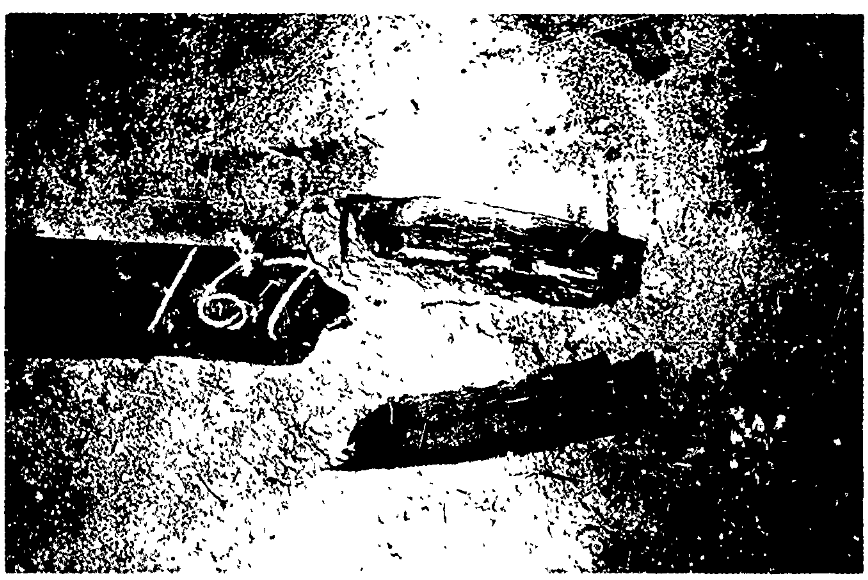


(b) J6283

(c) J6447

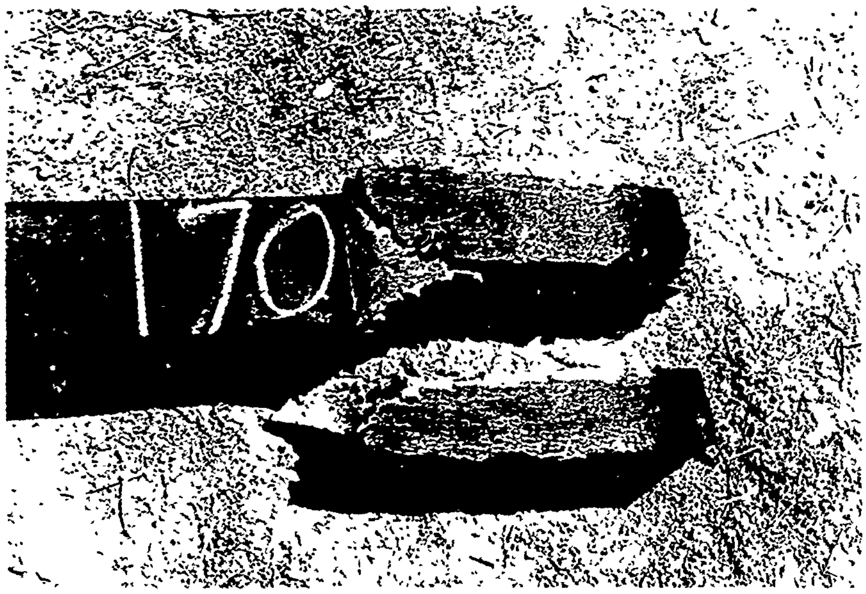
Fig. 40. Test setup shown in (a) and results in (b) and (c) for dual-explosive charges detonated to cut square steel bars from opposite sides.

J6264

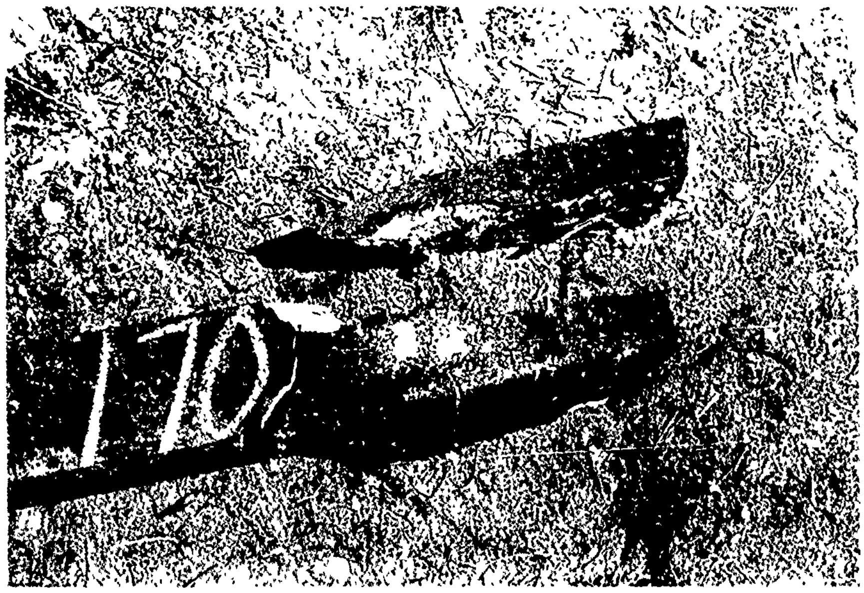


J6263

Fig. 41. End-primed 2-1/4-pound paste explosive charge (7/8 by 4 by 10 inches) used to cut 4-inch-square steel bar by major cross fracture.

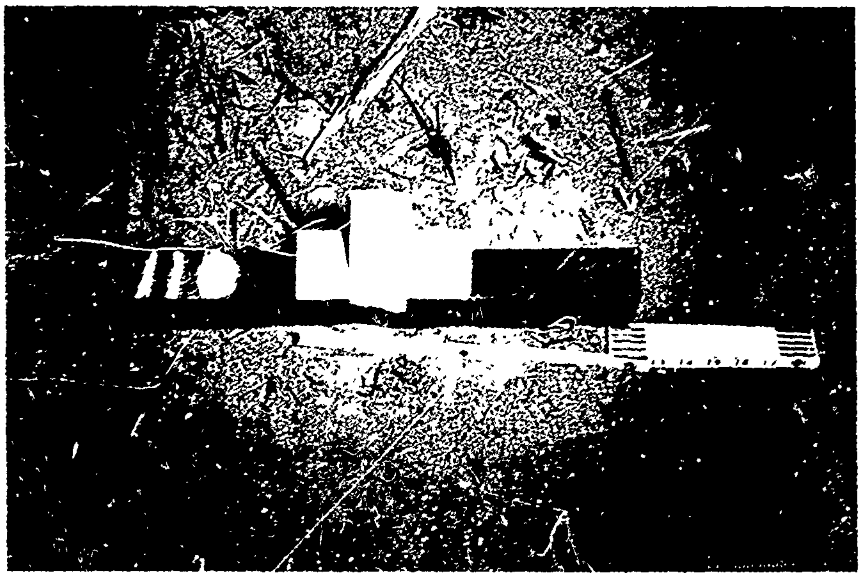


J6456

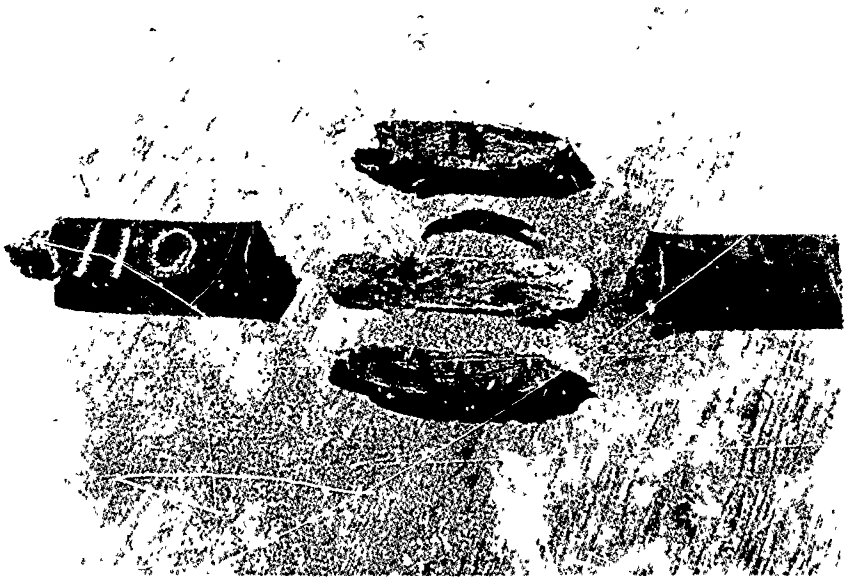


J6445

Fig. 42. Incomplete cross fracture (and longitudinal split) produced in 4-inch-square steel bar by end-detonated paste explosive charge (3/4 by 4 by 9 inches) of insufficient length and thickness.



(a) J6446



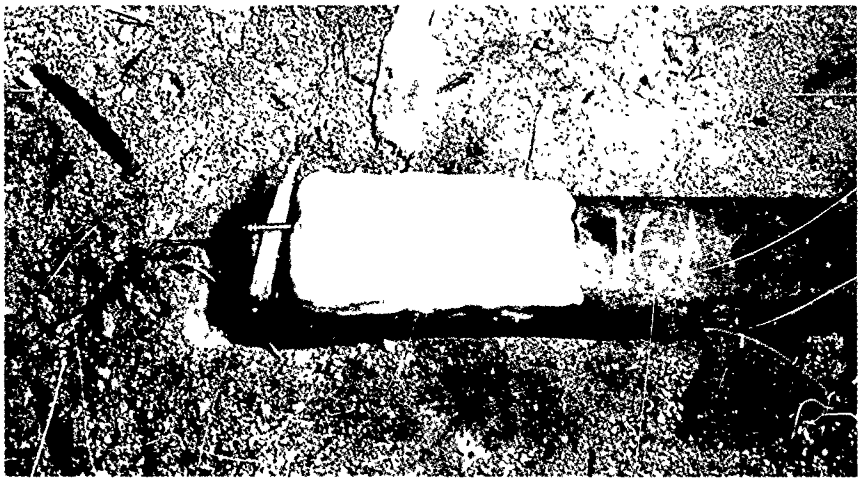
(b) J6450

Fig. 43. Center-primed C-4 explosive charge (0.84 pound in 1-3/8- by 2- by 6-inch configuration) used to break 2-inch-square steel bar by two cross fractures.

3, and 4 inches are contained in the summary of explosive-cutting test results in Appendix C. These experimental results are even less impressive than those for tests on square steel bars. Of the 40 test firings of explosive charges (37 employed the cross-fracture steel-cutting principle and 3 utilized dual-offset charges), only 13 round steel bars were completely cut. Cross-fracture steel-cutting explosive charges produced 11 of those 13 complete cuts. The excessive number of failures with the cross-fracture steel-cutting technique are attributed primarily to the inadvertent use of alloy-steel rods of only 18-inch lengths. The test results showed that 21 of the 26 incomplete cuts with the cross-fracture technique occurred on steel bars of 18-inch lengths. Only 5 failures occurred on round steel bars which had lengths greater than 18 inches, and use of charges with nonoptimum dimensions caused the failures of test shots 160, and 163 through 166 as recorded in Appendix C. The high strength of the alloy steel which requires more explosive for cutting than mild steel and the adverse effect of the soil-steel interface are considered secondary causes of the large number of incomplete cuts on round steel bars (3)(7). The test results revealed how the end boundaries of short steel bars can dissipate explosive shock and cause demolition failures with contact explosive charges.

The rectangular explosive charges placed and end-detonated along one side of the curved surfaces of the steel bars, severed them with cross-fracture splits similar to those on the square steel bars. Unlike the explosive effects on these bars, however, no spalling occurred on the free surfaces opposite the charges, and longitudinal splits where observable occurred only down the centers of the free surfaces (Figs. 44 and 45). Explosive charges of lengths exceeding the optimum charge lengths of 2-1/2 to 3 times the steel diameters, when detonated at the charge centers, broke the bars with cross fractures at both ends of the charges. Successful cutting of the round steel bars by the cross-fracture method was achieved with charges containing 31 to 87 percent of the explosive prescribed by the U. S. Army steel-cutting formulas. In one test shot on a bar, 5 feet in length, 4 inches in diameter, an overcharge of 125 percent of the explosive specified by the formula was intentionally used for comparison with results on 18-inch bars (test shots 155 and 156 in Appendix C).

c. Experiments with the Saddle Charge Steel-Cutting Technique. The saddle charge explosive-cutting technique was studied in 16 test firings on round mild steel bars which are 2, 4, and 6 inches in diameter

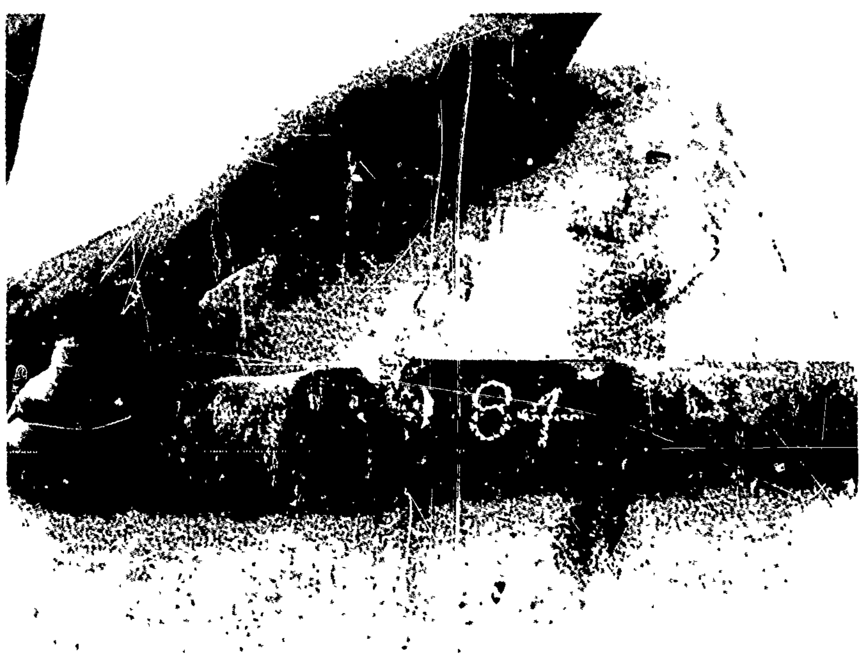


(a) J6367

(b) J6412

Fig. 44. Paste and C-4 explosive charges emplaced to cut round steel bars by cross-fracture technique. (a) 1-2/3-pound paste charge of 3/4 by 3-1/2 by 7-1/2 inches on 4-inch mild steel bar (test shot 161); and (b) 1-1/4-pound C-4 charge of 1 by 3-3/4 by 5 inches on 2-inch alloy steel bar (test shot 84).

J6366



J3971

Fig. 45. Round steel bars severed by cross fracture produced by explosion of contact explosive charges.

and 5 feet in length. An adaptation of the original SRI cross-fracture technique, the saddle charge technique utilized triangular-shaped explosive charges to cut steel bars by the end split formed in the steel at the base end of the triangular charges that were detonated at their apexes. Saddle charges, so named because they fit like a saddle along one side of round steel bars, were shaped as isosceles triangles to conserve explosives. The charges were prefabricated and evaluated by means of test procedures such as those described for the cross-fracture steel-cutting experiments. Figure 46 gives the specifications that were used for guidance in the fabrication, placement, and detonation of saddle charges. Experimental details that include dimensions and weights of the charges evaluated are given in Appendix C.

Fifteen of the sixteen saddle charges which contained only 14 to 49 percent of the C-4 explosive computed by the U. S. Army steel-cutting formulas, severed the round steel bars of 2-, 4-, and 6-inch diameters (Appendix C). A saddle charge with 33.25 percent of the prescribed explosive weight failed to sever a steel bar, 6 inches in diameter. In five subsequent tests, however, saddle charges of 46 to 48 percent of the prescribed quantity of explosive severed round steel bars, 6 inches in diameter. Saddle charges, shaped as triangles, had bases equal to one-half the circumferences of the bars, altitudes equal to twice the bases, and thicknesses of 2/3 inch. Because of the sharp-pointed triangular shape, which was awkward and cumbersome to tape and handle, saddle charges were more difficult to prefabricate and emplace than were the rectangular cross-fracture charges. The savings in explosive realized with saddle charges was not large enough to warrant the extra time necessary for their preparation and emplacement (Fig. 47).

11. <u>Steel-Cutting Experiments with Diamond Charge Technique.</u> Evaluation of the diamond charge technique for explosive cutting of steel bars involved the experimental firing of 56 diamond-shaped charges of Composition C-4 and EL506A-5 Detasheet explosives on both alloy and mild steel bars of 2- to 6-inch thicknesses. Although originally developed at Poulter Laboratories of SRI for cutting of round steel bars only, in this test program, the diamond charge technique utilized contact explosive charges of diamond shape to cut both round and square steel bars by tensile fractures induced through interactions of colliding stress wave fronts. Shaped for economy of explosive, the experimental charges were fabricated from sliced blocks of C-4 explosive or 10- by 20-inch sheets of Detasheet explosive. The specifications shown in Fig. 48 were used as a guide. As tested, the diamond charges were of 1/4- to 1-inch thickness, had long axes equal to the perimeters of the steel bars being attacked, and had short axes

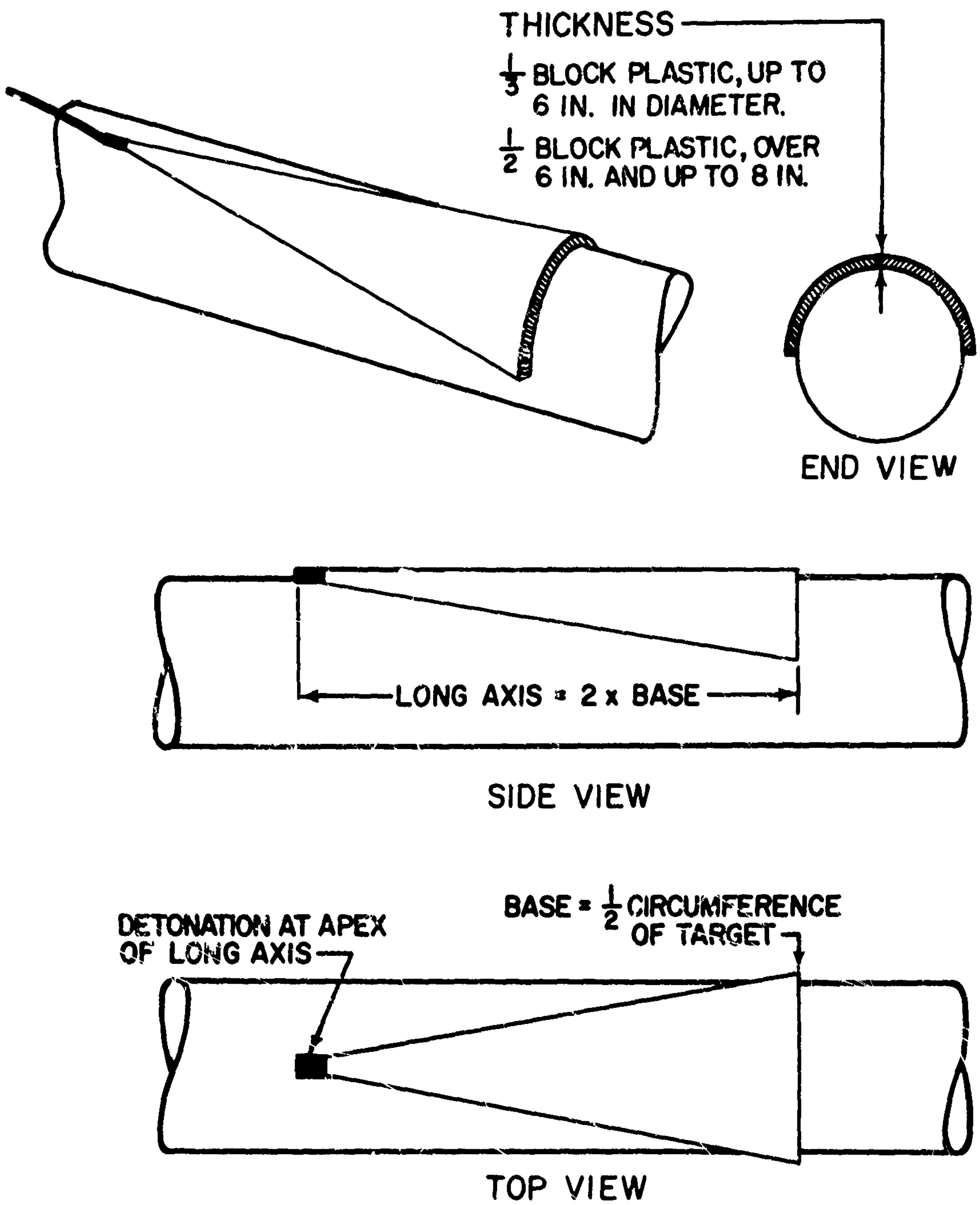
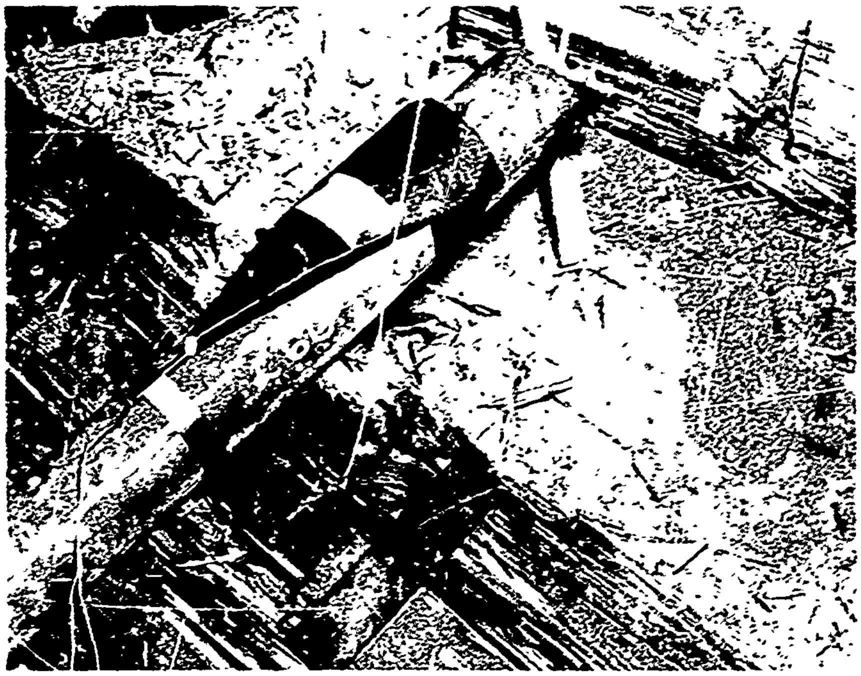
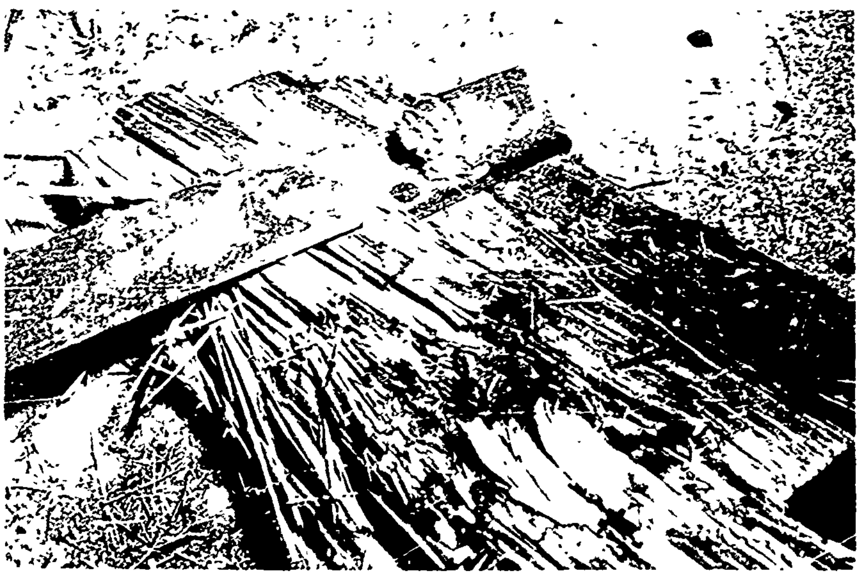


Fig. 46. Saddle charge explosive technique for cutting steel bars (taken from Field Manual, FM 5-25).



(a) K3087



(b) K1593

Fig. 47. Saddle-charge setup shown in (a) and test results in (b) on mild steel bar, 4 inches in diameter.

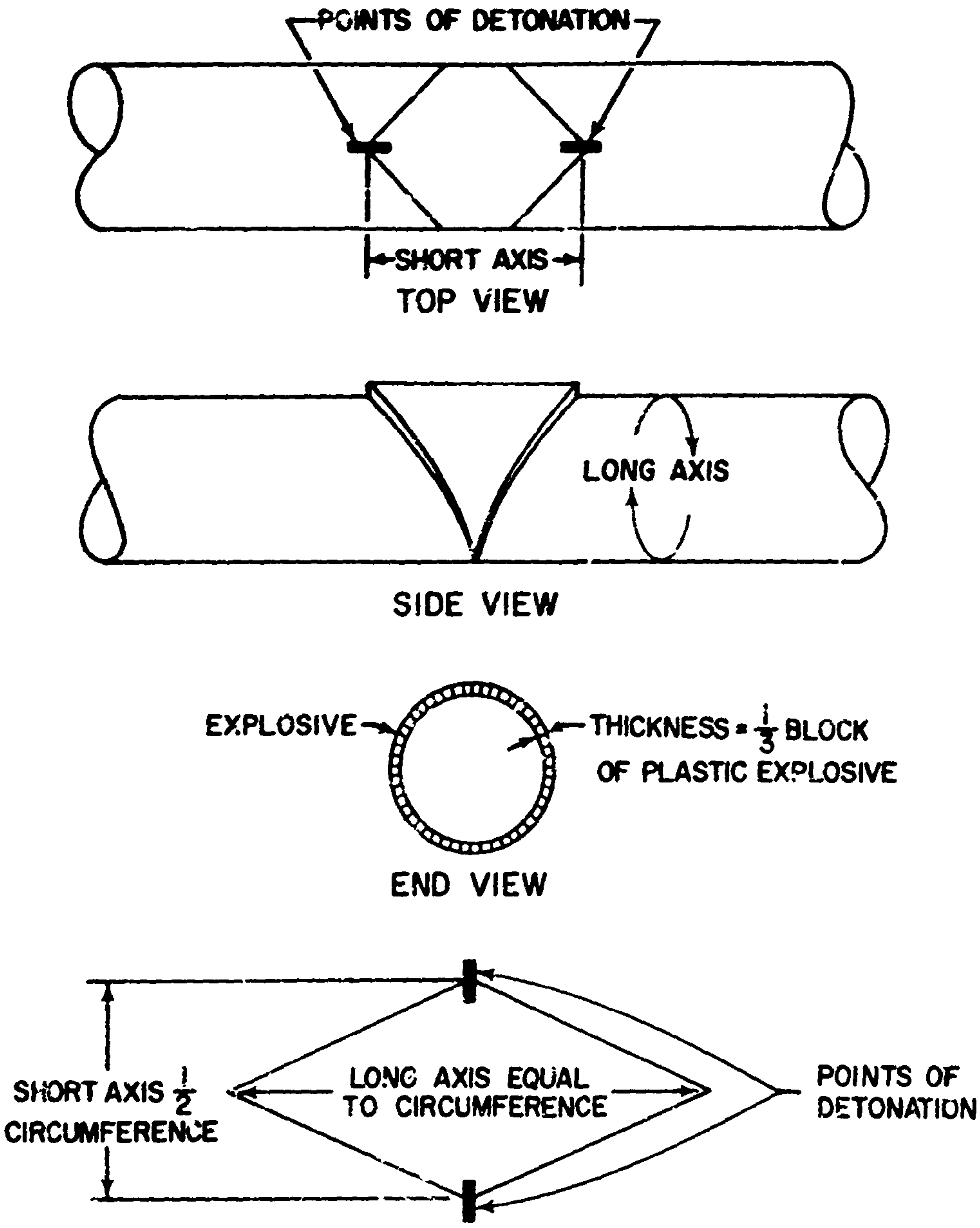
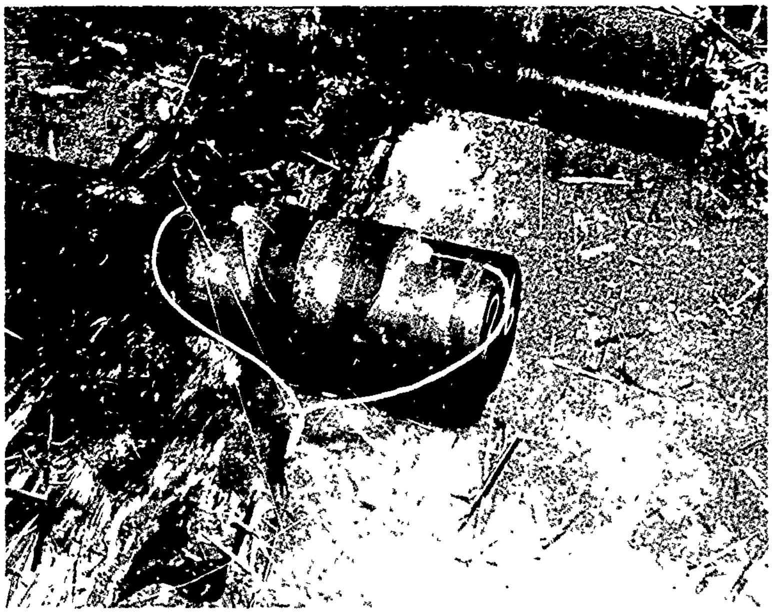


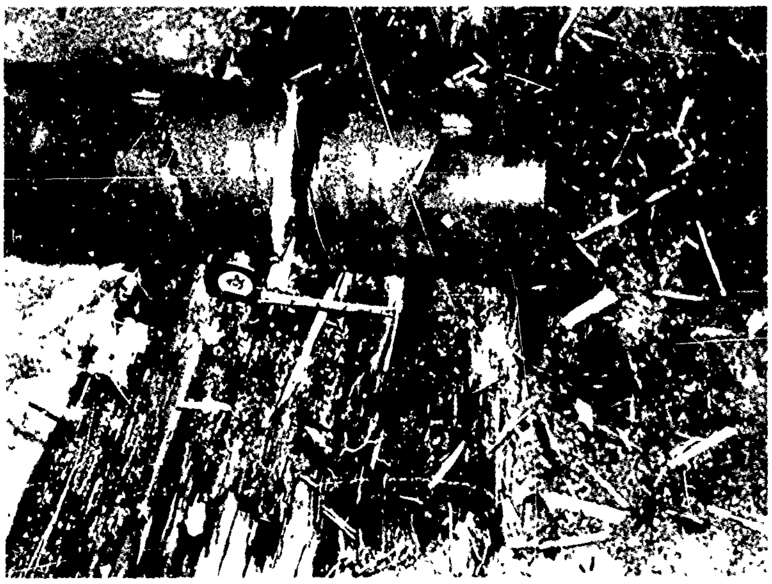
Fig. 48. Diamond charge explosive technique for cutting both round and square steel bars. (Note: Long axis is equal to circumference of round steel bars or perimeter of square steel bars; and short axis is equal to one-half circumference or perimeter.) (Taken from Field Manual, FM 5-25.)

equal to one-half the perimeters of the steel bars. Emplaced with the long axes of the diamonds (charge length) wrapped around the steel bars, the diamond charges, taped tightly to the steel bars, were detonated simultaneously at the two points of the short axes of the diamonds by either electric caps or detonating cord priming assemblies. Detonation from the points of the short axes of the diamond charges caused two explosive shock waves to travel through the steel to the center of the diamond charges where their collision and interaction produced reinforced stress waves that sheared the steel bars by a tensile fracture (2)(10)(18). Detonating cord priming assemblies provided more nearly simultaneous exact initiation at two points so that the two shock fronts collided more nearly at the center of the diamond-shaped charges and produced clean tensile fractures (Figs. 49 and 50). U. S. Army special electric caps, with variations of ± 5 milliseconds in times of initiation, yielded inexact center collision of the two stress waves that still cut the bars, but resulted in more jagged tensile fractures.

The diamond charge, steel-cutting technique, then, is an explosive demolition application of the stress wave method of cutting metals. Formation of tensile fractures in steel through the reflection and interaction of colliding stress wave fronts is the outstanding behavior factor associated with explosive stress waves (2). In this test program with diamond-shaped charges, the tensile fractures that severed the steel bars were formed in the steel at or near the centers of the diamond charges detonated from the two points of their short axes. The tensile fractures were initiated either on the free surface of the steel bars or in the interior of the bars because several incompletely cut steel bars contained tensile fractures on the free surface that had not propagated through to the charge surface of the steel (Figs. 51 and 52). In any event, the tensile fractures occurred at the locus of collision of the traveling detonation fronts, which was usually at the exact center of diamond charges detonated simultaneously with detonating cord priming assemblies. Variations in times of initiation between the two electric caps detonating the diamond-shaped charges caused the tensile fractures to occur off center under the charges because the shock front initiated by the earlier exploding cap had traveled further than the shock front initiated by the later exploding cap. The destructive effect of the diamond charge explosive technique has been attributed to the interaction of reinforced shear waves caused by the collision of the two traveling detonation fronts, which are said to yield tension in the proper orientation and of sufficient magnitude to produce tensile fractures in steel. Tensile fractures are said to occur where the induced stresses are elastic waves in which stresses exceed the yield strength of the steel (2).

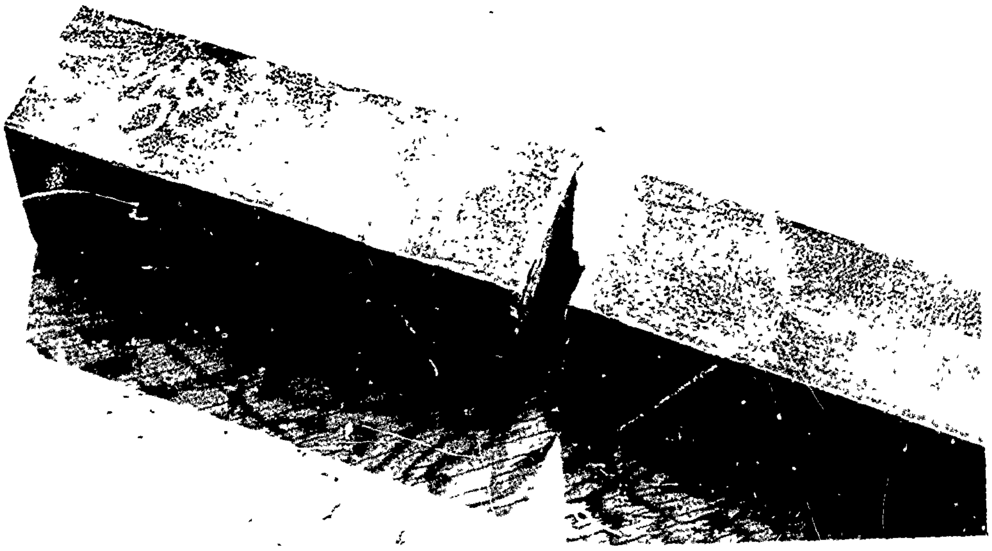


K3038

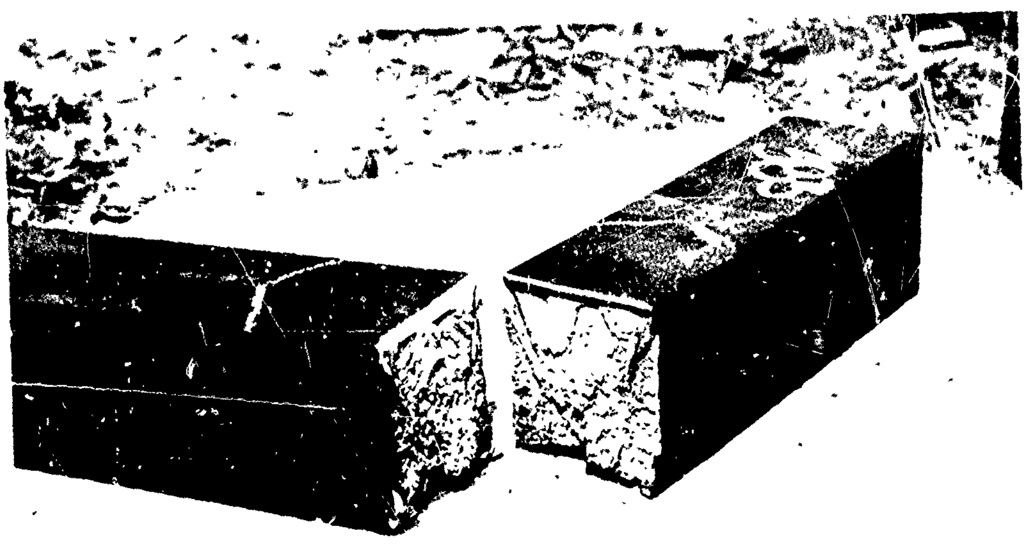


K3029

Fig. 49. Cutting of a round steel bar, 6 inches in diameter, by tensile fracture induced by diamond-shaped charge of EL506A-5 Detasheet explosive (0.90 pound in 3/16- by 9- by 18-inch diamond).

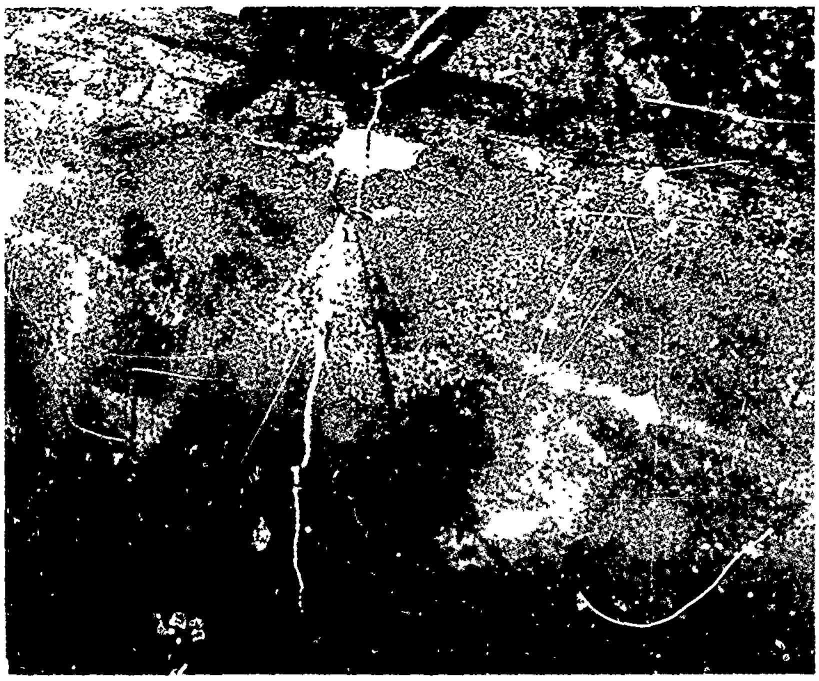


M5052



M5053

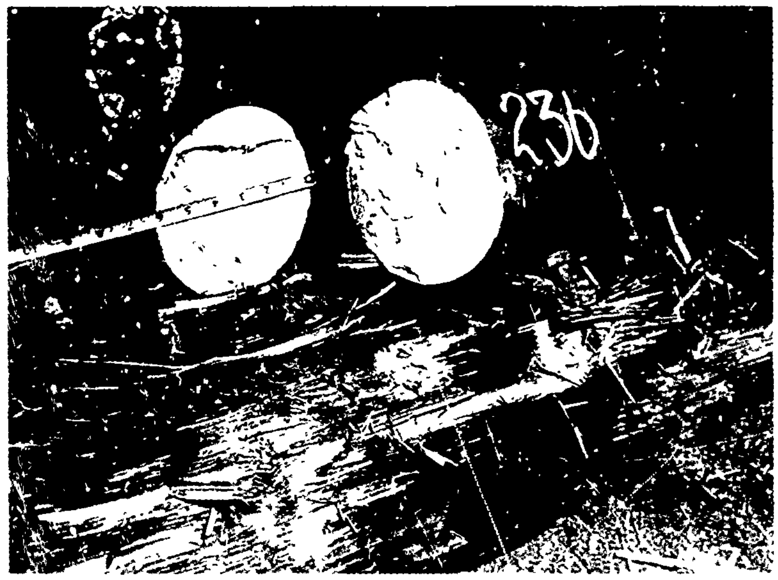
Fig. 50. Four-inch-square steel bar cut by a tensile fracture induced by diamond-shaped charge of Detasheet explosive (0.82 pound in a 3/16- by 8-1/2- by 17-inch diamond).



K3132

M5041

Fig. 51. Incomplete tensile fractures formed in round steel bars, 6 inches in diameter, and square steel bars, 4 inches in diameter, by means of diamond-shaped charges of insufficient dimensions and explosive weight (long axes did not completely encircle perimeters).



K3030

K3031

Fig. 52. Complete tensile fracture produced in steel bar, 6 inches in diameter, by means of diamond-shaped charge (1.23-lb C-4 explosive charge of 1/4 by 9 by 18 inches).

The summary of steel-cutting test results obtained with diamond-shaped charges, presented in Appendix C, shows that 39 of the 56 diamond-shaped charges severed the 2- to 6-inch-thick steel bars by tensile fractures. Two of the seventeen incomplete cuts occurred on 4-inch square steel bars because the long axes of the diamond-shaped charges did not completely surround the perimeters of the steel bars, and the other 15 incomplete cuts occurred on round steel bars. Of the 44 experimental firings on round steel bars, five out of five bars, 2 inches in diameter, seven out of seven bars, 3 inches in diameter, nine out of eleven bars, 4 inches in diameter, and nine out of twenty-one steel bars, 6 inches in diameter, were severed by these highly effective explosive-cutting charges which used only 04.36 to 43.94 percent of the explosive prescribed by the U. S. Army steel-cutting formulas. Of the 15 failures of the charges to cut round steel bars, two on rods, 4 inches in diameter, were caused by insufficient explosive, and a third was detonated too close to a free end so that the reflected shock wave apparently adversely affected the cutting effect of the diamond charge (8). The other 12 failures occurred on steel bars, 6 inches in diameter, four of which were alloy steel that required more explosive than was used for cutting; and eight in which excessively thin charges with long axes that did not completely encircle the circumference caused failures on mild steel bars. Table VII summarizes the test results with the diamond-charge steel-cutting techniques.

Table VII. Summary of Test Results with Diamond-Shaped Charges

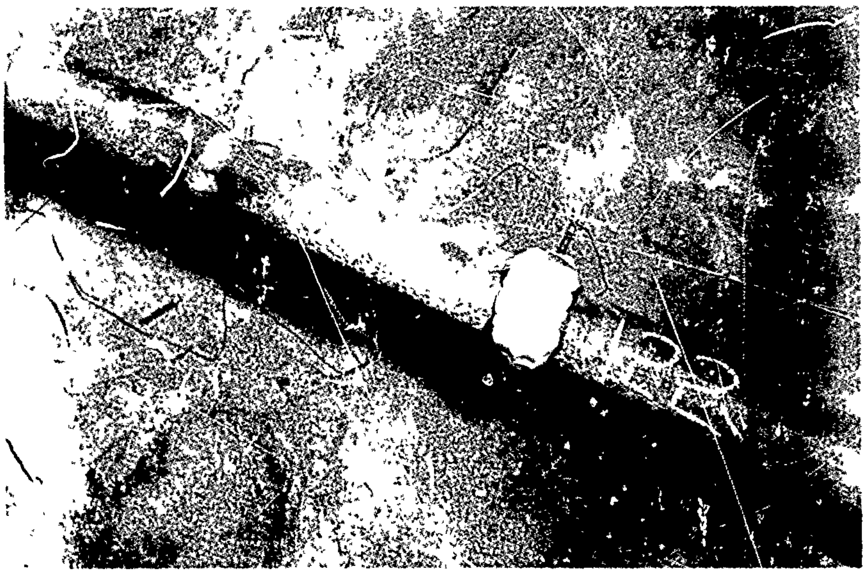
Diameter or Thickness of Steel Bar (in.)	Explosive Charge Prescribed by U. S. Army Formulas (lb)*	Range of Explosive Charge Weights Used (lb)	No. of Effective Cuts	No. of Ineffective Cuts
2	2.98	0.13 to 0.42	5	None
3	1.98	0.26 to 0.84	7	None
4 (Round)	3.52	0.41 to 1.43	9	2
4 (Square)	4.48	0.75 to 2.23	10	2
6	7.91	0.66 to 3.53	9	12

* Formula $P = \frac{D^2}{1.34}$ for calculation of charges to cut round steel bars, 2 inches in diameter; and formula $P = \frac{3/8\ A}{1.34}$ for computing charges to cut all other steel bars.

12. Explosive-Cutting Tests on Steel Pipe. Five paste explosive charges were detonated on thick-walled steel pipe to check the cutting effectiveness of paste explosive on that shape of steel. With a steel thickness of 0.436 inch, the pipe had a 2.375-inch outside diameter, a 1.503-inch inside diameter, and a 2.66-square-inch cross-sectional area (15). By the U S. Army steel-cutting formula $P = \frac{3/8\,A}{1.34}$, a 3/4-pound paste explosive charge was required to cut the pipe. Two charge placements and priming methods were investigated. In two test shots, a 1/2-inch-thick charge of paste explosive was placed completely around the 6.30-inch circumference of the pipe; one charge was 7/8 inch wide and the other was 1-3/4 inches wide. Both of these charges were detonated at one point by an electric blasting cap. Neither charge cut the thick-walled pipe, but simply collapsed the steel inward with a 3/8-inch-deep depression around its circumference With three test shots, the cross-fracture technique was utilized successfully to cut the pipe two times. The third test shot was a failure because the center-primed charge was not long enough for detonation at the center, which usually produces cross fractures in the steel at both charge ends; nevertheless, the pipe was almost severed. Had detonation been initiated from one end of the charge, as was so with the two successful test shots, the pipe would no doubt have been severed (Figs. 53 and 54). Details of these test shots are listed in Appendix C.

13. Description of Linear Shaped Charges. During this test program, a standard linear shaped charge of the West German Army and two USAERDL-fabricated linear shaped charges were evaluated. These charges were as follows.

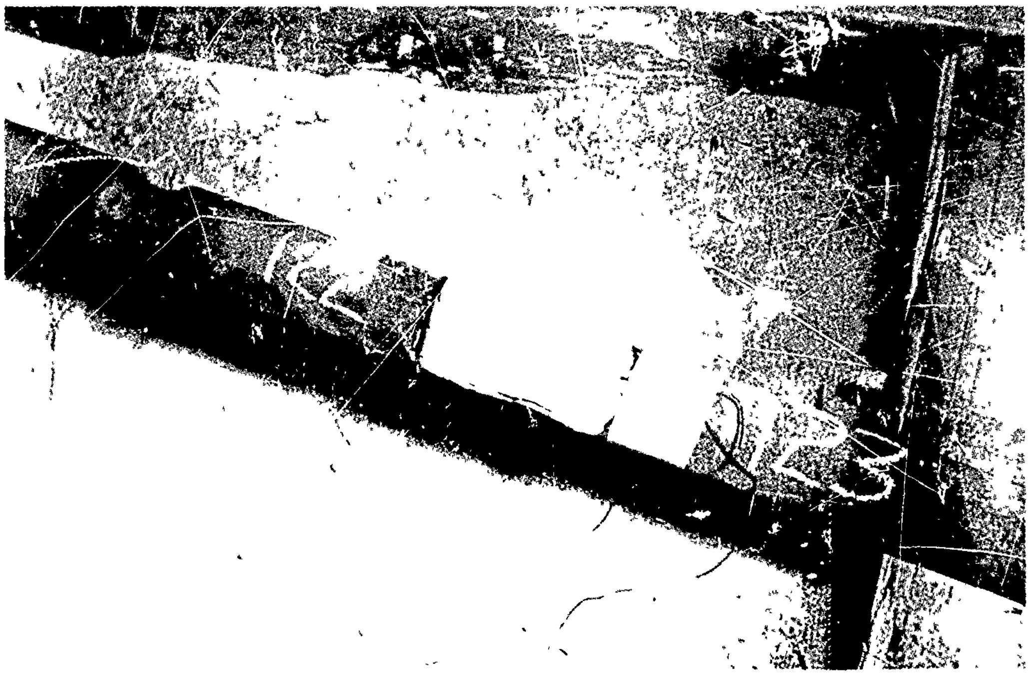
a. German Army Linear Shaped Charge, DM 19. The DM 19 linear shaped charge, a standard demolition material of the West German Army, weighed 39.16 pounds and contained 19.8 pounds of TNT/RDX explosive, in a 49/51 percent ratio, cast into a sheet metal container that had a hemispherical copper liner at one end and a threaded capwell for priming at the other end; another threaded capwell was located at one end of the charge near its top. These capwells received both the German electric and nonelectric blasting caps with priming adapters and U. S. Army standard blasting caps although the threads precluded use of U. S. priming adapters. The 8-inch-long 9-inch-wide, half-round copper liner gave the linear shaped charge its linear jet-forming capability. Two sliding sheet metal plates, which provided a 10-inch standoff distance when they were fully extended, were fastened in grooves on the sides of the charge. The charge had two holding clamps and two screws for connecting two charges; and by riveting the issue sheet metal tie plates to the sides or bottoms of bridges,



J6304

J6300

Fig. 53. Test setup and results for demolition of thick-walled steel pipe with paste explosive charge encircling circumference (incomplete cut).



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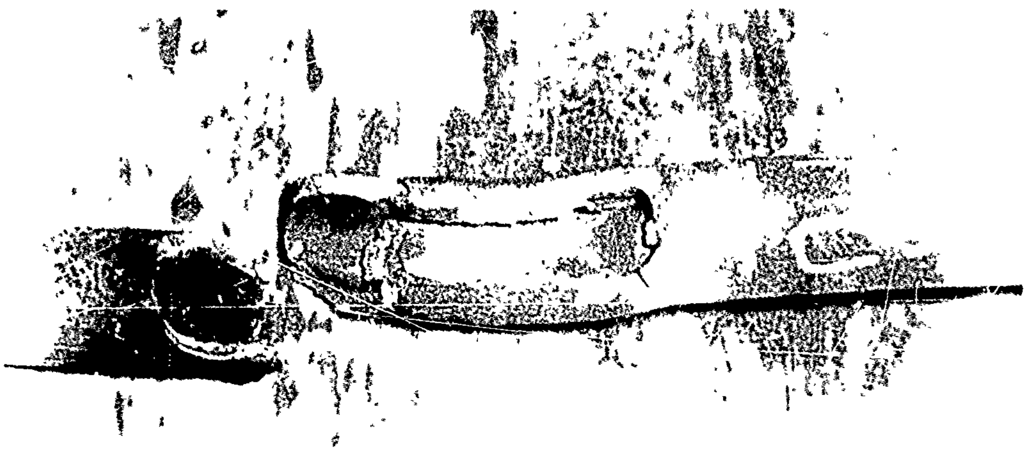


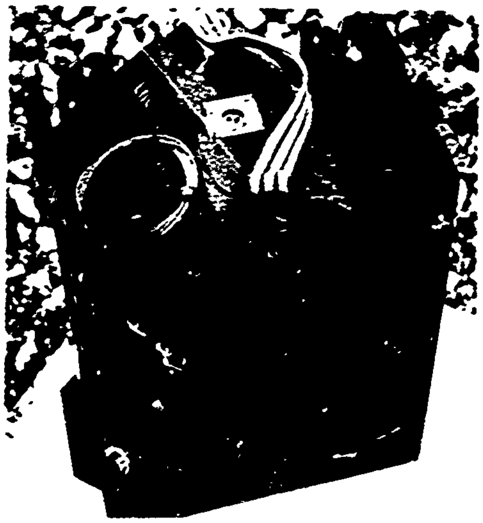
J6378

Fig. 54. Paste explosive charge severed thick-walled steel pipe by cross fracture.

any number of charges could be connected to form a linear shaped charge of the desired length. One blasting cap could be used to detonate one end of a line of the shaped charges. According to the German Army Manual, this charge was capable of cutting 78.74 inches of unreinforced concrete, 29.53 inches of reinforced concrete, and 11.81 inches of steel, with the linear cut being equal to the length of the charge (19). If two charges were placed and detonated diametrically opposite to each other on both sides of the target, the depth of cut could be doubled. Each DM 19 shaped charge was packed separately in a wooden frame which utilized the charge-carrying strap for movement of the complete package (Fig. 55).

b. Large USAERDL Linear Shaped Charges. USAERDL personnel designed and fabricated linear shaped charges from 21-gage sheet metal and 1/8- and 3/16-inch-thick copper sheeting; Composition C-4 explosive was used as the explosive filler. Eight-inch-long by 4-5/16- to 6-1/2-inch-wide sheet metal containers had 8-inch half-round linear copper liners soldered into one end to give the charges a jet-forming capability. Two flanged plates attached to the sides of the charges provided the correct standoff distances from the target and also served as the base for riveting the charges to the target with a rivet-punching powder-actuated driver. Composition C-4 explosive was hand loaded into the charge containers on top of the liners to heights of 3 to 5 inches above the liner apexes. Fifteen-gram PETN boosters embedded into the top and one side of the explosive filler insured detonation when they were initiated by U. S. Army special electric blasting caps (Fig. 56).

c. Small USAERDL Linear Shaped Charges. Small linear shaped charges loaded with Composition C-4 explosive were fabricated from standard Mark 7, Model 7 demolition charge containers of sheet metal used by U. S. Army Explosive Ordnance Disposal units as linear shaped charges to open steel cases of bombs, shells, rockets, and mines (20)(21). Two containers, each in the form of a 6-inch rectangle of 3/4-inch width and 1-inch height with a wedge-shaped cavity liner and metal legs, were spot-welded together to form a 12-inch linear shaped charge capable of making line cuts in steel, concrete, or like material. The wedge-shaped metal trough at the bottom of the container gave the charge the capability to form linear jets of metal particles when about 1/2 pound of C-4 explosive hand tamped into the 12-inch containers was detonated by a blasting cap butted vertically against the center of the explosive filler. The legs provided the correct standoff from the target so that the jet could form properly before impacting the target. Four small commercial magnets, fastened to the standoff legs, held the linear shaped charges to steel beams along the desired line of cut (Fig. 57).



L9681

L9680

L9679

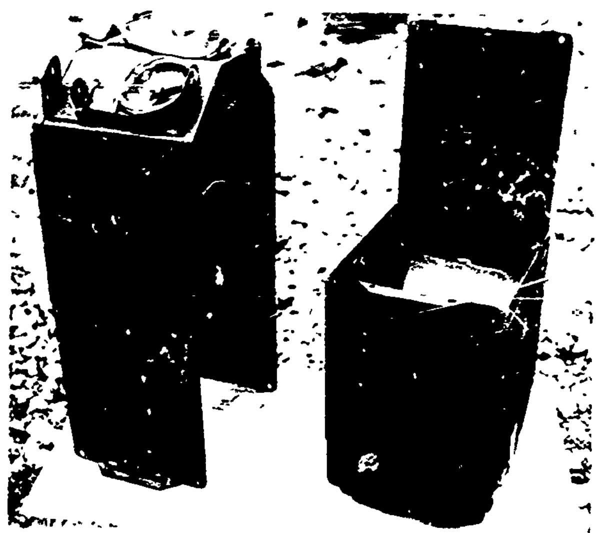
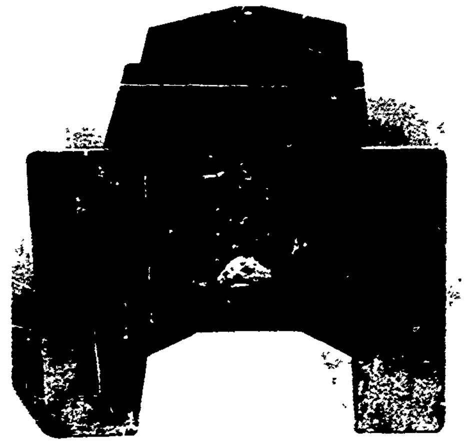
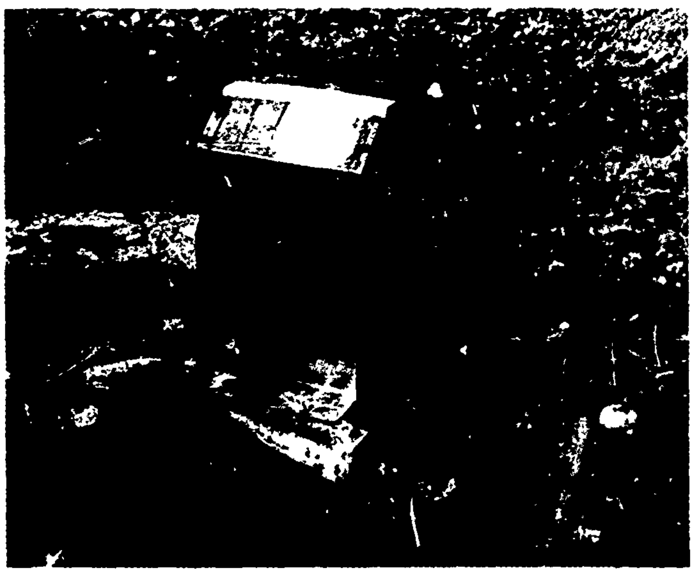


Fig. 55. West German Army Linear Shaped Charge, DM 19.

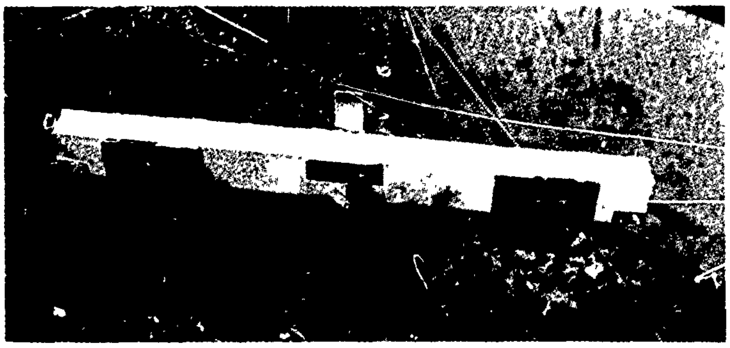


(a) L2990 (b) L2994



(c) L3044

Fig. 56. USAERDL-fabricated linear shaped charge (large size). (a) Sheet metal container and linear copper liner; (b) container with linear copper liner inserted; and (c) linear shaped charge loaded with C-4 explosive and primed for detonation at right end.



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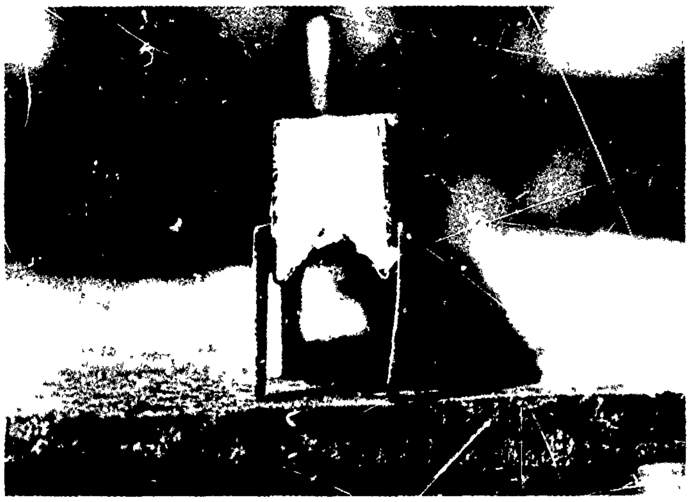

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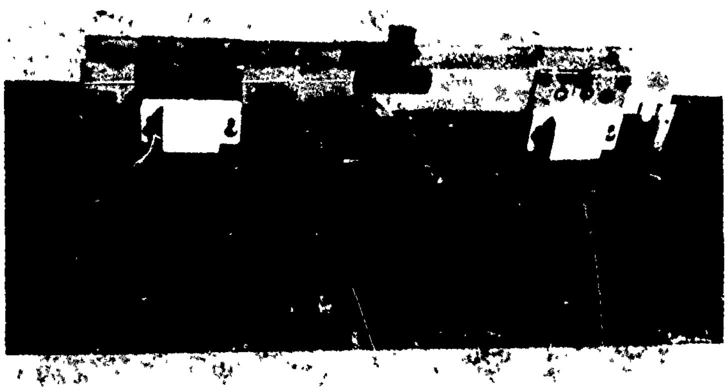


J4377

Fig. 57. Small linear shaped charges fabricated from Mark 7 demolition charge containers and commercial magnets.

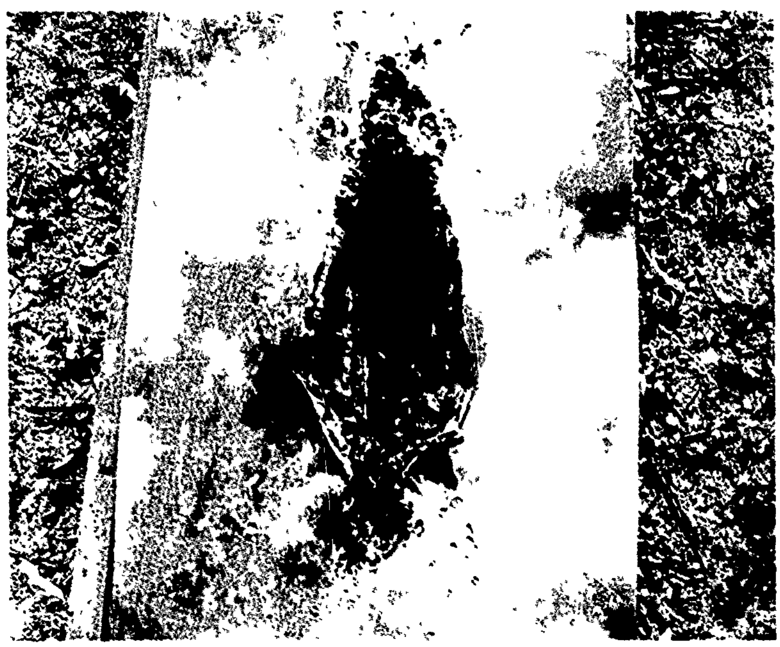
14. Steel-Cutting Experiments with Linear Shaped Charges. Linear shaped charges were evaluated for steel cutting in 33 experimental firings on steel plates and wide-flange beams. Experimental procedures and results were as follows:

a. DM 19 Lincar Shaped Charges. Eight West German Army DM 19 linear shaped charges were exploded against a stack of six 3-inch-thick alloy-steel plates placed horizontally on level ground. Four charges were detonated singularly, three by end initiation and one by center initiation, and in two test shots multiples of two DM 19 charges were connected and detonated by end initiation of one charge with an electric cap. Detonated with the linear cavities facing the steel plates, the shaped charges formed jets of metal liner particles that made line cuts in the steel plates. The depths, widths, and lengths of the linear cuts determined the effectiveness of these charges for cutting steel.

Single DM 19 German Army linear shaped charges produced line cuts of 3-1/4- to 4-3/4-inch depths, 4-1/4- to 4-3/4-inch widths, and 10- to 12-inch-lengths in steel plates; multiples of two DM 19 shaped charges yielded linear cuts of 5-inch depths, 4-3/4- to 5-inch widths, and 19-1/2- to 20-1/2-inch lengths. These charge yields are not impressive when considered in relation to the amount of explosive involved. The 3/16-inch-thick copper liner of the DM 19 charges is apparently too thick for formation of optimum jets required for maximum cutting effect because large shards of the metal liner were found in the line cuts on the steel plates. Rivets securing the sheet metal containers also probably interfered with formation of optimum cutting jets (Fig. 58).

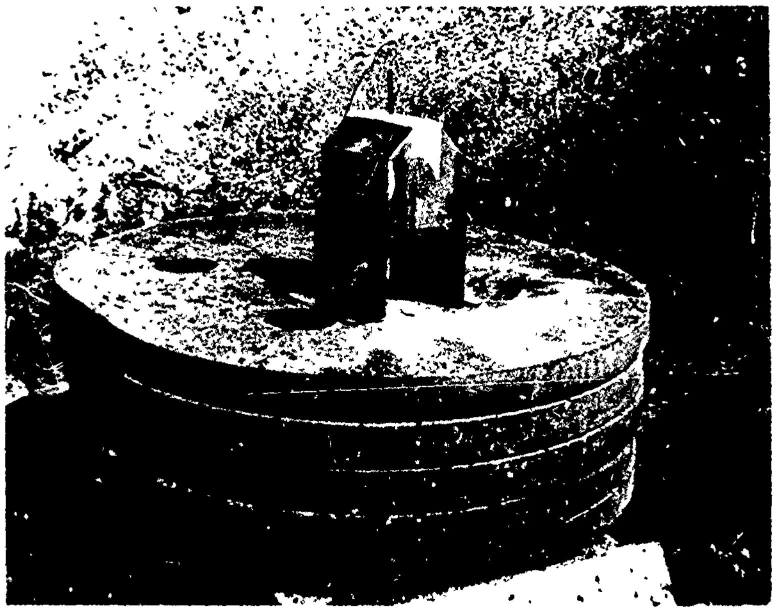
b. Large USAERDL Linear Shaped Charges. Evaluated as single charges on stacked alloy-steel plates, as described previously, USAERDL linear shaped charges that contained 5.0 to 9.6 pounds of hand-loaded C-4 explosive produced linear cuts in the steel with dimensions about equal to cuts made by the DM 19 German charges. The eight linear shaped charges yielded line cuts of 3-3/8- to 4-1/2-inch depths, 3-3/8- to 4-3/4-inch widths, and 11- to 14-inch lengths. It is considered significant that these locally fabricated linear shaped charges, which contained only 1/4 to 1/2 the explosive of the DM 19 German charge, produced line cuts with dimensions comparable to those made by DM 19 linear shaped charges. The characteristics of both the West German Army DM 19 linear shaped charge and the USAERDL-fabricated linear shaped charges, together with the dimensions of the line cuts made in steel plates by those charges (Fig. 59), are given in Appendix C.

L9668

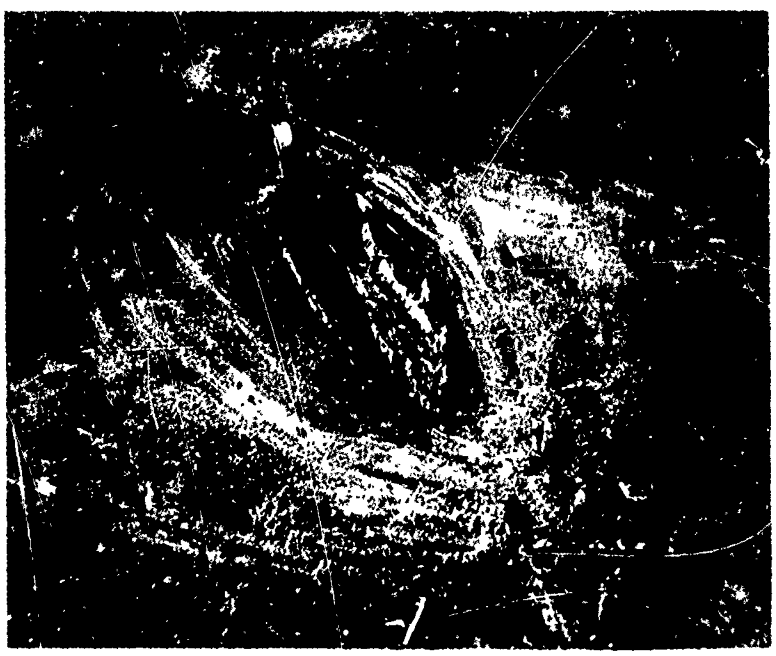


L9672

Fig. 58. Typical test setup and results of DM 19 linear shaped charge firings on steel plates.

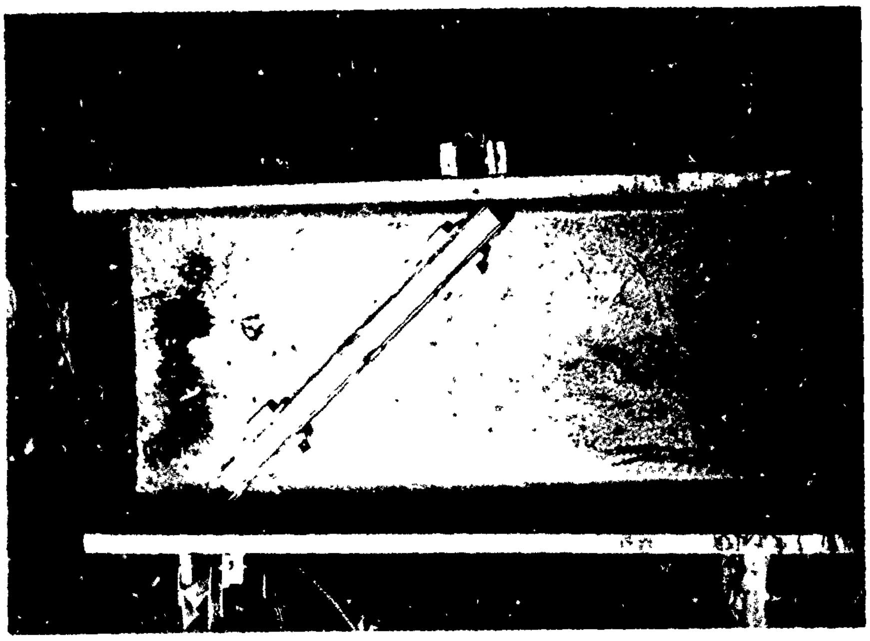


L3038

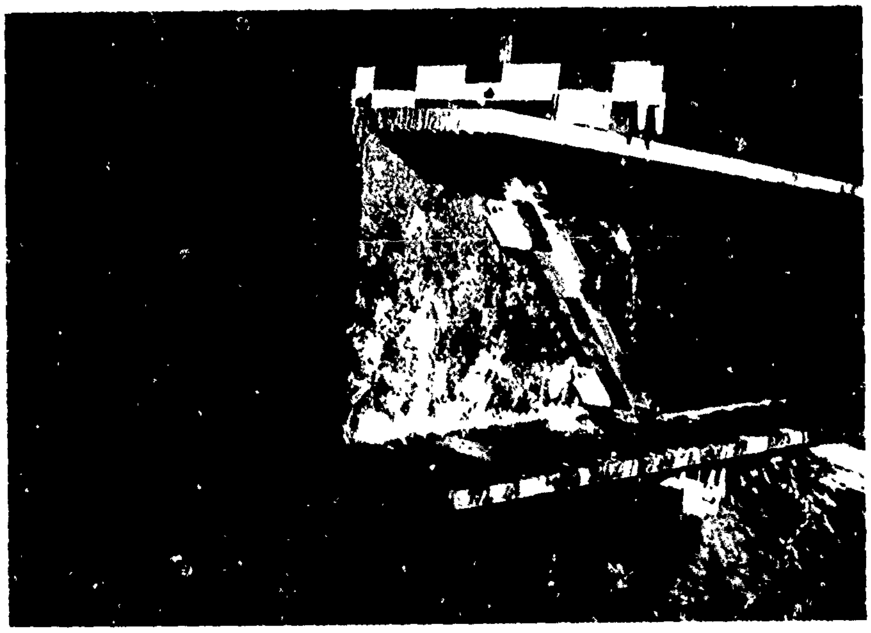


L3029

Fig. 59. Typical test setup and results of USAERDL linear shaped charge firings on steel plates.



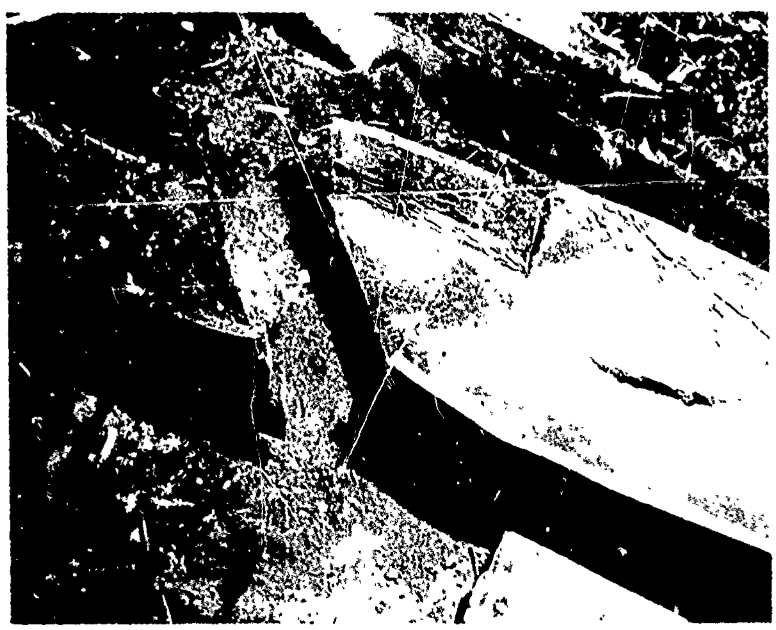
J4371



J4375

Fig. 60. Emplacement of small linear shaped charges for cutting 10WF49 steel beams.

c. <u>Small USAERDL Linear Shaped Charges</u>. Small linear shaped charges of 12-inch lengths that contained an average of 1/2 pound of C-4 explosive were used in 17 test shots to sever 10WF49 steel beams with cross-sectional areas of 14.4 square inches. Three linear shaped charges, fabricated from standard U. S. Army linear shaped charge containers and primed with electric blasting caps were detonated simultaneously to sever a steel beam through the cutting effect of the jet formed from the wedge-shaped trough of the steel containers. Attached to the steel by magnets, one 12-inch charge placed diagonally along the beam web and a second and third charge placed one across each flange at the ends of the diagonal web charge completely cut the steel beams when the three charges were exploded simultaneously by electric caps in a series circuit. The linear shaped charge jets severed the beams with a diagonal cut. Cutting of the 10WF49 wide-flange beam by conventional U. S. Army demolition methods would have expended 4-1/2 pounds of C-4 explosive. Although each 12-inch charge held 1/2 pound of explosive, only about 1-1/10 pounds of explosive was actually used to cut the beams because the two flange charges were centered on and overhung the 7-1/8-inch flanges of the beams. Seventeen complete cuts were made on the steel beams with 51 linear shaped charges (Figs. 60 and 61).



J4367

Fig. 61. Typical cut made on 10WF49 steel beam by jets from small linear shaped charges.

III. DISCUSSION

15. Evaluation of Test Results. Here, experimental data are considered as results of explosive-cutting tests on either structural steel shapes or steel bars because the 10 demolition experiments can be grouped into those two categories according to the similarity of techniques employed for destruction of steel shapes. Steel angles, beams, channels, and plates were cut with linear explosive charges, and the longitudinal split was employed as the destructive mechanism for those structural steel shapes. Steel pipes, and both round and square bars were severed by the cross-fracture split in which either rectangular or triangular shaped saddle charges were used. A form of stress wave cutting of steel, diamond-shaped charges utilized on round steel bars, and the offset charges used to shear cables and square bars were all contact explosive charges, the effectiveness of which should be compared with that of the cross-fracture charges. The analysis, then, revealed that the shape of the steel member being cut fixes the destructive explosive mechanism, either the longitudinal split, the cross-fracture split, the shearing break, or the stress wave tensile fracture, that must be employed for its demolition. Hence, during this experimental program, four explosive demolition techniques on steel targets of two general shapes were evaluated. Evaluation of linear shaped charges for steel cutting comprised only 33 experiments that have been discussed previously. The other experiments involved several methods of calculation, placement, priming, and initiation of charges of three kinds of explosives. Hence, in the evaluation the effects of those factors believed to be critical in explosive demolitions are considered. Explosive demolitions such as weapons require optimum employment for maximum destructive effect.

a. Significance of Explosive. A high explosive with great brisance is necessary for maximum cutting effect on steel by contact charges (2)(3)(7). Brisance is the shattering power of an explosive as distinguished from its total work capacity, which is a function of the total heat liberated at the instant of explosion. The rate at which the heat-energy is liberated determines the explosive power. Because the shattering power of an explosive is dependent upon the suddenness with which the products of explosion are liberated, the rate of detonation is a major factor in determining its brisance; other influential factors are density and dimensions of the explosive charge. The higher the rate of detonation, therefore, the greater will be the shattering power of brisance of the explosive (2). Of the three test explosives, Composition C-4 at a density of 1.57 grams per cubic centimeter had a detonating velocity of about 26,000 feet per second, paste explosive had a detonating velocity of about 24,000 feet per second at a density of 1.52 grams per cubic centimeter, and the EL506A-5 Detasheet explosive had a detonating velocity of 23,616 feet per second at a density of 1.48 grams per cubic centimeter (12). It is evident from this comparison that Composition C-4 explosive, with its higher rate of detonation, should be more effective for steel cutting than the other two explosives.

The results of factorial experiment 1 (Table II) show that Composition C-4 explosive was significantly more effective than paste explosive in the modified Plate Dent Test which was conducted to measure the ability of the two explosives to compress solid steel. Although no actual shattering by the explosives were involved in that test, they produced deformations in the steel that are recognized as being closely related to brisance of explosives (4). In the modified Plate Dent Test, the volumes of deformations were measured and used as measurements of the charge yields in a statistical analysis of variance. The analysis of variance (Appendix B) revealed that Composition C-4 explosive produced significantly larger deformations in the plates than did paste explosive and should therefore be more effective for steel cutting. EL506A-5 Detasheet flexible explosive was not available for evaluation in the modified Plate Dent Test, so it must be evaluated on the basis of its performance in 62 tests on steel angles, beams, channels, and steel bars.

It is apparent, therefore, that Composition C-4 with a higher density and rate of detonation than either paste or EL506A-5 Detasheet explosive had greater shattering ability which enhanced its cutting performance and reliability. Likewise, the density of the C-4 explosive, which was sliced to specified charge dimensions, was more uniform than that of the semifluid paste explosive which contained oil bubbles that varied its density. Oil bubbles in the paste explosive charges, especially those placed with a caulking gun extruder, probably adversely affected the detonating velocity and shock wave propagation with consequent reduction in the steel-cutting effect of the paste explosive. Variations in the dimensions of the paste explosive charges also likely reduced its shattering ability because exact charge shapes could not be maintained with that semifluid explosive. With both hand placement and mechanical extrusion, the perimeters of the charges and their thicknesses were slightly irregular, but the charge weights were exact to plus or minus a gram. Moreover, although EL506A-5 Detasheet explosive had invariable density, its density was considerably lower than that of Composition C-4 explosive as was its detonating velocity, so pound for pound that explosive would have to be less effective than C-4 explosive for steel cutting. The thin sheets of the EL506A-5 explosive with their flexibility and formability, however, made it ideal for steel cutting and compensated to a large degree for its lower density and rate of detonation. It was superior to C-4 explosive for steel cutting on the basis of adaptability to irregular target shapes and of the ease and simplicity with which it was handled, cut, and shaped to almost any charge configuration.

Although Composition C-4 explosive with its higher density and rate of detonation and, consequently, its greater brisance was somewhat more effective and reliable than the other two explosives, the difference in effectiveness was not great enough to warrant adjustment by a relative effectiveness factor as is U. S. Army practice. On a comparative basis of complete cuts versus incomplete cuts, C-4 explosive was more reliable than either paste or EL506A-5 explosive (Table VIII). The larger number of incomplete cuts with paste explosive was attributed primarily to the adverse effects of low-density charges with varying dimensions; these effects were less prevalent with the hand-placed paste explosive charges that were compressed slightly in the normal course of emplacement. With the EL506A-5 Detasheet explosive, lack of intimate contact with the steel and the use of excessively thin charges caused the large number of incomplete cuts. More care had to be exercised in the placement of the EL506A-5 explosive charges which were more difficult to secure with masking tape because the pliable strips of explosive tended to pull away from the steel. Paste explosive was easiest to place by hand, and it adhered better to steel than either of the other explosives, although C-4 explosive was quickly emplaced and adhered well to grease-coated steel.

On an overall basis, though, the three test explosives were considered about equal on either a weight or ratio of charge width to thickness basis for steel cutting. Other factors critical in explosive cutting of steel, such as better contact with the steel for paste explosive and the closer control of explosive thickness possible with the Detasheet explosive, combined to compensate for the greater shattering ability of C-4 explosive. Although the comparison of the steel-cutting effectiveness of the three explosives illustrated in Table VIII is based on nonstatistical cut or no cut experimental procedures, the comparison is believed valid because the data resulted from extensive testing of the explosive techniques in which standard U. S. Army demolition practices were used. It is emphasized that except for the factorial experiments in which the charge weights were controlled but charge thicknesses varied, the explosive weights of actual test charges could not be held constant for like charge dimensions of all three explosives because they had different densities. The charge sizes were also computed in inches in relation to the steel thicknesses and not in pounds related to the cross-sectional areas.

b. Tests on Structural Steel. The results of the experimental firing of 237 explosive charges on steel plates, angles, channels, and

Table VIII. Comparative Effects of the Three Test Explosives

Type of Steel Target	Paste Explosive				C-4 Explosive				EL506A-5 Explosive			
	No. of Test Shots	No. of Cuts	Percentage of Reliability	Range in Percentage of Calculated to Actual Charges for Complete Cuts	No. of Test Shots	No. of Cuts	Percentage of Reliability	Range in Percentage of Calculated to Actual Charges for Complete Cuts	No. of Test Shots	No. of Cuts	Percentage of Reliability	Range in Percentage of Calculated to Actual Charges for Complete Cuts
Steel Plate	40	23	42½	16 to 66	31	26	84	29 to 42	27	24	89	05 to 16
Steel Angle	10	10	100	21 to 28	4	4	100	27 to 32	4	4	100	24
Wide-Flange Beam	69	49	71	20 to 38	30	26	87	15 to 38	7	4	57	21 to 32
Steel Channel	7	7	100	19 to 22	4	4	100	20 to 22	4	4	100	20 to 22
Square Bar	28	16	57	49 to 88	15	8	53	25 to 75	None	None	None	None
Round Bar	22	8	36	38 to 126	34	20	59	14 to 93	None	None	None	None
Round and Square Steel Bars (cut with diamond-shaped charges)	None	None	None	None	36	28	78	5 to 44	20	11	55	5 to 19

wide-flange beams were evaluated during the analyses presented in this report. The evaluation was conducted on the test data contained in Appendix C, which lists results from 98 tests on steel plates, 18 tests on steel angles, 15 tests on steel channels, and 106 tests on wide flange beams. Of the 237 explosive charges tested, the results showed 185 complete cuts of the steel test members and 52 failures in which the steel targets were not completely cut. Twenty-five of the incomplete cuts occurred on steel plates, and the other 27 incomplete cuts occurred on wide-flange beams. The analysis fixed the causes of those incomplete cuts and described changes in the explosive techniques that eliminated them. Demolition procedures utilized for calculation, placement, priming, and detonation of the steel-cutting explosive charges are analyzed here in that order.

Structural steel shapes were the demolition targets for this phase of testing; hence, in the analyses, the cutting effects of linear explosive charges with rectangular cross sections detonated in contact with the steel along the desired line of cut was considered. Linear explosive charges utilized the destructive effect of the longitudinal split for cutting steel.

(1) Charge Calculation Methods. Four different formulas were employed either for computation of the actual test charges or for comparison of the test charges with explosive charges computed by the other formulas, particularly the present U. S. Army formula for structural steel. As previously described, the U. S. Army formula $P = \frac{3/8\ A}{1.34}$, for calculation of steel-cutting charges, computes only the weight of explosive in pounds and does not fix the configuration or dimensions of the charge or its placement position on the target. Determination of those critical factors, which can determine the success or failure of explosive demolition of any target regardless of the quantity explosive involved, are left to the discretion of user troops, who may or may not have adequate knowledge of their optimum employment. The SRI formula $C_T = 1/2\ S_T + 1/8$ with $C_W = 4\ C_T$, or its modification $C_T = 1/2\ S_T$ with $C_W = 3\ C_T$ determine the optimum configuration and dimensions of the required charge in relation to the steel thickness to be cut. Those formulas also fix the charge placement and position on the target as well as the points of charge initiation, another important factor in explosive demolition which the U. S. Army formula fails to prescribe. In fixing the shape and dimensions of the required explosive charge, its placement position on the target, and prescribing its point of initiation, the SRI and modified SRI formulas automatically compute the amount of explosive

necessary for effective demolition. By establishing those significant factors of explosive demolition for the user, the formulas minimize the chance of demolition failure as determination of the charge shape dimension, placement, and priming are not left to guesswork, chance, or unreliable procedures.

In Table IX, the actual explosive charges used for completely cutting the steel members are compared with the charges prescribed for those same members by the U. S. Army and SRI steel-cutting formulas. This table gives the maximum and minimum size charges, their thicknesses, widths, and explosive weights, used successfully to sever the structural steel shapes listed in the first column at the left side. The number of complete cuts shown for the various steel shapes represent the total number of complete cuts achieved with explosive charges having characteristics equal to or between those of the maximum and minimum size charges. Explosive weights of both maximum and minimum size charges are shown in relation to the cross-sectional area of the steel member that was cut; this cutting relationship is given in terms of pounds of explosive relative to a fraction of the cross-sectional area of the steel to provide a comparison with the U. S. Army steel-cutting formula, P = 3/8 A. As an example, for complete cuts on 1 by [illegible]-inch steel plates with minimum size charges of 1.37 pounds in 1- by 2- by 12-inch dimensions, the actual cutting relationship of pounds of explosive to area of steel was P = 1/8 A, or pounds of explosive equalled 1/8 of the cross-sectional area. This cutting relationship, which is only one third of the present U. S. Army formula P = 3/8 A for structural steel, was determined first as a percentage of the actual explosive charge weight in relation to the area of steel and then converted to the nearest common fraction. All conversions were rounded up to the common fraction listed, so the relationships given include adequate safety factors to compensate for minor imperfections in charge placement. With an even larger safety margin to allow for the fact that these test procedures exercised greater care than normal for field operations, the experimental data still reveal an approximate 200 percent overcharge for contact charges of Composition C-4 and other explosives of similar power computed by the U. S. Army formula $P = \frac{3/8\ A}{1.34}$. A formula of P = 1/5 or P = 1/8 A would suffice even if the results of the first tests on steel plates with soil interfaces were to be considered as unbiased.

Test results with Detasheet and C-4 explosive charges detonated on 1- to 3-inch steel plates that had free surfaces

Table IX. Comparison of Experimental Data Taken from Explosive-Cutting Tests o

Structural Steel			Charge Calculated by Army Formula (lb) (b)	Charge Calculated by SRI Formula (c)		Characteristic of Actual Char		
						Maximum Size Charge		
Shape	Thickness (in.) (a)	Area (sq in.)		Thickness and Width (in.)	Weight (lb)	Thickness and Width (in.)	Weight (lb)	Relation of Experimental Weight to Steel Area
1 x 6-Inch Steel Plate	1	6.00	1.68	5/8 x 2-1/2	0.54	11/16 x 2-1/2	0.37	P = 1/16 A
1 x 10-1/2-Inch Steel Plate	1	10.50	2.93	5/8 x 2-1/2	0.94	3/4 x 2-1/2	0.95	P = 1/14 A
1 x 12-Inch Steel Plate	1	12.00	3.35	5/8 x 2-1/2	1.07	1-1/8 x 2	1.54	P = 1/7 A
3/4 x 12-Inch Steel Plate	3/4	9.00	2.52	1/2 x 2	0.68	1-1/16 x 2	1.54	P = 1/5 A
9/16 x 4-3/4-Inch Steel Plate	9/16	3.56	0.99	13/32 x 1-5/8	0.19	13/16 x 1-1/4	0.41	P = 1/11 A
1/2 x 12-Inch Steel Plate	1/2	6.00	1.68	3/8 x 1-1/2	0.39	13/16 x 2	1.11	P = 1/5 A
1/4 x 12-Inch Steel Plate	1/4	3.00	0.84	1/4 x 1	0.18	3/8 x 2	0.44	P = 1/6 A
1 x 18-Inch Steel Plate	1	18.00	5.05	5/8 x 2-1/2	1.60	1/2 x 1-1/2	0.86	P = 1/20 A
1/2 x 18-Inch Steel Plate	1/2	9.00	2.52	3/8 x 1-1/2	0.58	1/4 x 1	0.31	P = 1/29 A
1/4 x 18-Inch Steel Plate	1/4	4.50	1.26	1/4 x 1	0.26	1/4 x 1/2	0.18	P = 1/20 A
3 x 18-Inch Alloy Steel Plate	3	5.40	15.12	1-5/8 x 6-1/2	10.80	1-9/16 x 4-1/2	7.49	P = 1/7 A
5 x 3-1/2 Steel Angle	1/4	2.06	0.58	1/4 x 1	0.12	13/16 x 1-1/8	0.38	P = 1/5 A
8 x 8 Steel Angle	1-1/8	16.73	4.68	11/16 x 2-3/4	1.80	11/16 x 2-3/4	1.48	P = 1/11 A
15 x 3-3/8 Steel Channel	F-5/8 W-3/4	14.64	4.12	F-7/16x1-3/4 W-1/2x2	1.12	F-15/32x1-3/8 W-9/16x1-11/16	0.88	P = 1/16 A
16WF50 Steel Beam	F-5/8 W-3/8	14.70	4.11	F-7/16x1-3/4 W-5/16x1-1/4	0.96	F-5/8x2-1/4 W-5/8x1-3/4	1.37	P = 1/10 A
10WF49 Steel Beam	F-9/16 W-3/8	14.40	4.03	F-13/32x1-5/8 W-5/16x1-1/4	0.95	F-9/16x1-1/4 W-9/16x1-1/4	1.37	P = 1/10 A
14WF74 Steel Beam	F-13/16 W-7/16	21.76	6.09	F-17/32x2-1/8 W-11/32x1-3/8	1.64	F-17/32x2-1/2 W-11/32x1-3/8	2.00	P = 1/10 A
24WF76 Steel Beam	F-11/16 W-7/16	22.37	6.26	F-15/32x1-7/8 W-11/32x1-3/8	1.51	F-9/16x1-7/8 W-3/8x1-3/8	1.76	P = 1/12 A
36WF300 Steel Beam	F-1-11/16 W-15/16	88.17	24.76	F-31/32x3-7/8 W-19/32x2-3/8	9.77	F-1x3 W-11/16x2	7.73	P = 1/11 A
14WF426 Steel Beam	F-3-1/16 W-1-7/8	125.25	35.05	F-1-21/32x6-3/4 W-1-1/16x4-1/4	24.52	F-1-3/4x4-1/2 W-1-1/4x3-1/8	13.27	P = 1/9 A

(a) "F" and "W" signify flange and web, respectively.

(b) Army demolition formula, $P = \frac{3/8\ A}{1.34}$, was used where P = pounds of Composition C-4, paste, or EL506A-5 Detasheet explosive, required.

(c) SRI formula $C_T = 1/2\ S_T + 1/8$ and $C_W = 4\ S_T$ was used; where C_T = charge thickness, S_T = steel thickness, and C_W = charge width; all dimen Length of charge was equal to lengths of cuts being made on steel members (e.g., on wide-flange beams it was equal to depth of web plus widths the data presented in Appendix C show the exact dimensions of the steel members).

(d) Footnote (c) at end of this table gives an explanation of lengths of charges.

(e) One complete cut on a 1 x 10-1/4 steel plate and one complete cut on a 4 x 3-1/2 steel angle are not included.

nparison of Experimental Data Taken frc n Explosive-Cutting Tests on Structural Steel

s	Area (sq in.)	Charge Calculated by Army Formula (lb) (b)	Charge Calculated by SRI Formula (c): Thickness and Width (in.)	Charge Calculated by SRI Formula (c): Weight (lb)	Characteristic of Actual Charge Used for Complete Cut (d) — Maximum Size Charge: Thickness and Width (in.)	Maximum Size Charge: Weight (lb)	Maximum Size Charge: Relation of Experimental Weight to Steel Area	Minimum Size Charge: Thickness and Width (in.)	Minimum Size Charge: Weight (lb)	Minimum Size Charge: Relation of Experimental Weight to Steel Area	No. of Complete Cuts (e)
	6.00	1.68	5/8 x 2-1/2	0.54	11/16 x 2-1/2	0.37	P = 1/16 A	5/8 x 1-11/16	0.27	P = 1/20 A	6
	10.50	2.93	5/8 x 2-1/2	0.94	3/4 x 2-1/2	0.95	P = 1/14 A	5/8 x 2-1/2	0.72	P = 1/11 A	2
	12.00	3.35	5/8 x 2-1/2	1.07	1-1/8 x 2	1.54	P = 1/7 A	1 x 2	1.37	P = 1/8 A	6
	9.00	2.52	1/2 x 2	0.68	1-1/16 x 2	1.54	P = 1/5 A	3/4 x 1-1/2	0.72	P = 1/12 A	5
6	3.56	0.99	13/32 x 1-5/8	0.19	13/16 x 1-1/4	0.41	P = 1/11 A	13/16 x 1-1/4	0.41	P = 1/11 A	2
	6.00	1.68	3/8 x 1-1/2	0.39	13/16 x 2	1.11	P = 1/5 A	3/4 x 1	0.55	P = 1/10 A	5
	3.00	0.84	1/4 x 1	0.18	3/8 x 2	0.44	P = 1/6 A	1/2 x 1	0.34	P = 1/8 A	3
	18.00	5.05	5/8 x 2-1/2	1.60	1/2 x 1-1/2	0.86	P = 1/20 A	1/2 x 1-1/2	0.75	P = 1/20 A	10
	9.00	2.52	3/8 x 1-1/2	0.58	1/4 x 1	0.31	P = 1/29 A	1/4 x 3/4	0.21	P = 1/42 A	15
	4.50	1.26	1/4 x 1	0.26	1/4 x 1/2	0.18	P = 1/20 A	1/8 x 3/8	0.06	P = 1/75 A	11
	5.40	15.12	1-5/8 x 6-1/2	10.80	1-9/16 x 4-1/2	7.49	P = 1/7 A	1-1/2 x 4-1/2	6.92	P = 1/7 A	7
	2.06	0.58	1/4 x 1	0.12	13/16 x 1-1/8	0.38	P = 1/5 A	9/16 x 1-1/8	0.18	P = 1/11 A	4
	16.73	4.68	11/16 x 2-3/4	1.80	11/16 x 2-3/4	1.48	P = 1/11 A	1/2 x 2-1/2	0.99	P = 1/16 A	13
	14.64	4.12	F-7/16x1-3/4 W-1/2x2	1.12	F-15/32x1-3/8 W-9/16x1-11/16	0.88	P = 1/16 A	F-3/8x1-3/8 W-9/16x1-11/16	0.77	P = 1/19 A	15
	14.70	4.11	F-7/16x1-3/4 W-5/16x1-1/4	0.96	F-5/8x2-1/4 W-5/8x1-3/4	1.37	P = 1/10 A	F-3/8x3/4 W-9/32x3/4	0.56	P = 1/20 A	35
5	14.40	4.03	F-13/32x1-5/8 W-5/16x1-1/4	0.95	F-9/16x1-1/4 W-9/16x1-1/4	1.37	P = 1/10 A	F-1/2x1 W-1/2x1	1.01	P = 1/14 A	8
16 6	21.76	6.09	F-17/32x2-1/8 W-11/32x1-3/8	1.64	F-17/32x2-1/2 W-11/32x1-3/8	2.00	P = 1/10 A	F-3/8x2-1/8 W-11/32x1-3/8	1.46	P = 1/14 A	10
16 6	22.37	6.26	F-15/32x1-7/8 W-11/32x1-3/8	1.51	F-9/16x1-7/8 W-3/8x1-3/8	1.76	P = 1/12 A	F-1/2x1-1/2 W-11/32x1-3/8	1.26	P - 1/16 A	12
/16 6	88.17	24.76	F-31/32x3-7/8 W-19/32x2-3/8	9.77	F-1x3 W-11/16x2	7.73	P = 1/11 A	F-3/4x2 W-1/2x1-1/2	4.25	P = 1/20 A	7
6 8	125.25	35.05	F-1-21/32x6-3/4 W-1-1/16x4-1/4	24.52	F-1-3/4x4-1/2 W-1-1/4x3-1/8	13.27	P = 1/9 A	F-1-1/2x4 W-1x3	11.75	P = 1/10 A	7

ively.

ised where P = pounds of Composition C-4, paste, or EL506A-5 Detasheet explosive, required.

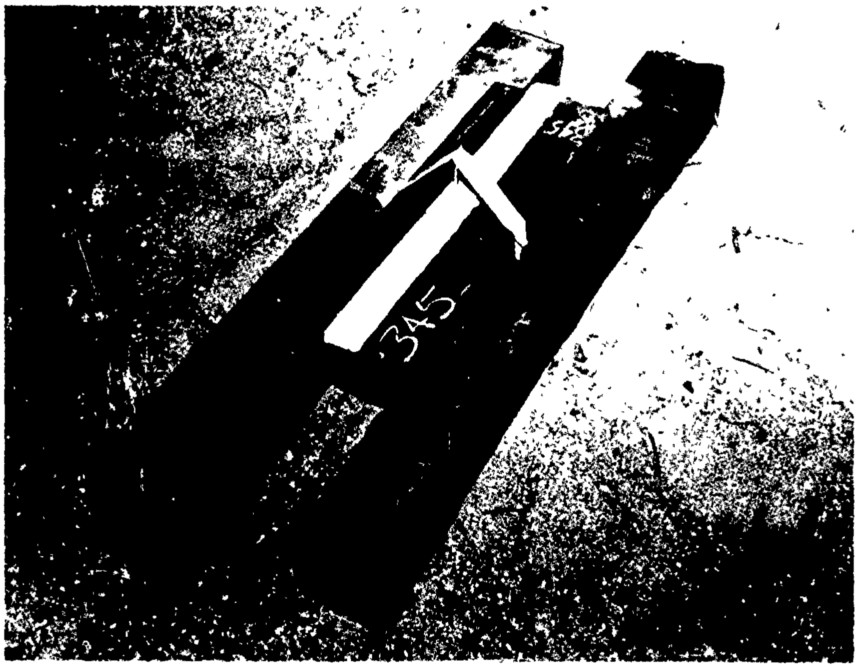
T was used; where C_T = charge thickness, S_T = steel thickness, and C_W = charge width; all dimensions are in inches.
being made on steel members (e.g., on wide-flange beams it was equal to depth of web plus widths of four half flanges;
ct dimensions of the steel members).

anation of lengths of charges.

nd one complete cut on a 4 x 3-1/2 steel angle are not included.

opposite the charges, however, revealed that results of those first experiments on steel plates were biased and that significantly more explosive was required to cut steel plates laid on the ground. As portrayed in Table IX, the Detasheet and C-4 explosive charges yielded more reliable and improved cutting effects on steel plates with free reflection surfaces with ·· ss explosive expenditure than did charges detonated on steel plates with steel-soil interfaces. With 100 percent reliability, 0.75- to 0.86-pound C-4 explosive charges severed 1-inch-thick mild steel plates of 18 linear inches in 10 test firings (Fig. 62). In comparison, 1.37- to 1.54-pound charges of C-4 or paste explosives, about twice as much explosive, were required to sever only 12 linear inches of 1-inch-thick mild steel plate that had soil-steel interfaces on the reflection surfaces. These results prove that significantly more explosive is required to cut thicknesses of steel with unfree reflection surfaces than is necessary to cut like steel which has free reflection surfaces. The closer the impedance match between the steel and the interface material on the reflection surface the greater will be the quantity of explosive needed for satisfactory demolition (2). Analyses of the test data for explosive cuts on 1/4- to 1-inch-thick steel plates disclose that severing of steel plates with soil-steel interfaces on the reflection surfaces required about two to three times the explosive used to sever 50 percent longer plates of similar steel thicknesses with free reflection surfaces.

The analyses of variance performed on the charge yields from the four factorial explosive tests on steel plates proved statistically the significant effects of charge width and thickness on the steel-cutting performance of contact explosive charges (Appendix B). Those statistical analyses further revealed that optimum ratio of charge width to charge thickness was between 2:1 and 4:1 and that explosive weight did not affect charge yields as significantly as did explosive width and thickness. For example, paste explosive charges of 151 and 175 grams in 1/2-inch thicknesses and 2-inch widths (test shots 17 and 22 of Table II) produced larger deformations in the steel than a 202-gram charge of 1-inch thickness by 1-3/8-inch width (test shot 7). Composition C-4 explosive charges of 1/2-inch thicknesses by 2-inch widths that weighed 168 grams (test shot 34) and 162 grams (test shot 30) gave greater yields than 1-inch-thick by 1-3/8-inch-wide charges of 234 (test shot 48) and 230 grams (test shot 30). Table II experimental data show other examples that demonstrate the importance of maintaining optimum ratios of charge widths to thicknesses for steel-cutting explosive charges.



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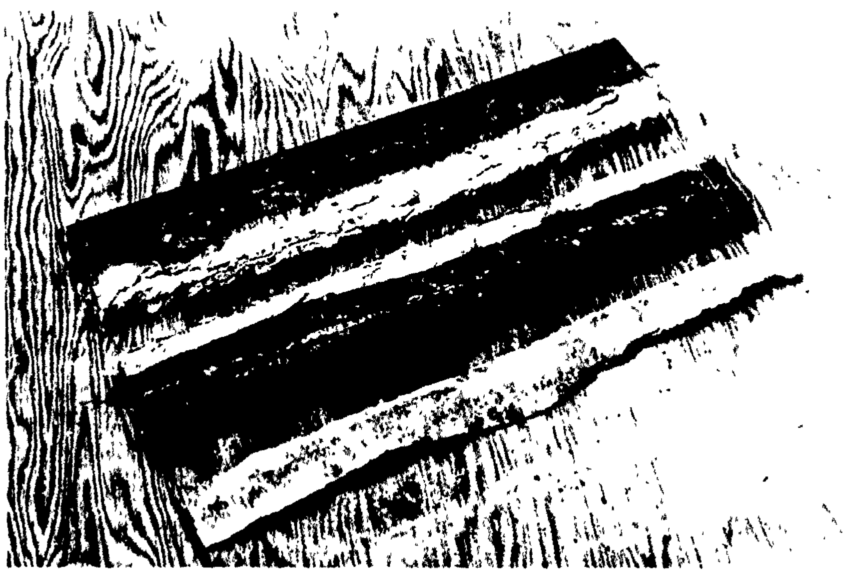

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Fig. 62. One-inch-thick mild steel paste of 18 linear inches with free reflection surface severed by 0.78-pound C-4 explosive charge (1/2 by 1-1/2 by 18 inches).

Experimental data summarized in Table IX, in addition, show that a 3:1 ratio of charge width to charge thickness is about optimum for contact explosive charges used to cut structural steel. As these data illustrate, the SRI formula, which prescribes a 4:1 ratio of charge width to charge thickness was satisfactory for computing charges to cut structural steel with thickness up to about 1-1/2 inches. On steel thicknesses exceeding 1-1/2 inches and up to 3-1/16 inches, the thickest steel cut in this test program, the SRI formula prescribed explosive charges that would have contained about two times more explosive than was actually used for complete cuts on wide flange beams and steel plates. The SRI formula prescribed thicker and wider charges than were used to cut structural steel with linear charges of the three test explosives. Having excessive widths and thicknesses, the charges computed by the SRI formula consequently contained excessive quantities of explosive. The SRI formula, for example, prescribed a 24.52-pound explosive charge for cutting a 14WF426 steel beam, and charges of 1-21/32-inch thickness by 6-3/4-inch width were used to cut the steel flanges of 3-1/16-inch-thick steel; yet in 7 test firings, explosive charges of 11.75 to 13.27 pounds total weight that had thicknesses of 1-1/2 to 1-3/4 inches and widths of 4 to 4-1/2 inches completely cut those heavy steel beams (Table IX gives the dimensions of web charges). A 36WF300 steel beam with a flange thickness of 1-11/16 inches was also completely cut 7 times with charges computed by the modified formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$. These contain only one-half to two-thirds of the amount of explosive computed by the SRI formula. Experimental data in Table IX show many other examples in which minimum size charges used to cut steel targets contained significantly less explosive and were much narrower than charges prescribed by the SRI formula. These data show that the SRI formula is fairly accurate for computation of charges to cut structural steel shapes of small and medium sizes; but for large steel beams, like meter beams used on bridges in foreign countries, the SRI formula prescribes charges of excessive explosive weight, primarily because the prescribed charges are too wide.

Thus, because explosive charges fabricated to the exact specifications calculated by the modified formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ have completely cut 1/4- to 1-inch-thick mild steel plates and 3-inch-thick alloy-steel plates with a high degree of reliability in 49 experimental firings (test shots 339 to 394 recorded in Appendix C) in addition to like satisfactory results on steel beams, that formula is considered more accurate than the SRI formula for computation of contact explosive charges to cut structural steel shapes. The SRI formula should be used to compute contact explosive charges for cutting alloy-steel plates like the 3-inch-thick steel plates of 18-inch lengths cut during the last phase of the test program. Those steel plates composed of high-strength nickel-alloy steel required more explosive for reliable cutting than had been used on structural steel.

Moreover, as the modified formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ specifies an explosive charge having an optimum ratio of width to thickness of 3:1, charges computed by that formula show a significant reduction in explosive weight over the SRI formula with its 4:1 ratio or the U. S. Army formula with no prescribed ratio. Yet the 3:1 ratio formula retains an adequate safety margin to compensate for moderate discrepancies in charge emplacement as demonstrated by 3:1 ratio charges of C-4 explosive that in six of seven test shots cut 3-inch-thick nickel-alloy steel, which requires more explosive for cutting than structural steel (3). The graph in Fig. 63 shows a comparison of the explosive charges calculated by both the U. S. Army and the SRI formulas, for cutting 1- to 3-1/2-inch-thick steel with charges calculated by the $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ modified formula for similar steel thicknesses. Charges computed by all three formulas are for cutting 18 linear inches of steel. The curve for the formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$, which is the actual cutting relation for complete cuts on 1- to 3-inch-thick steel plates of 18-inch length, prescribes a 3-1/2-pound explosive charge for cutting 18 linear inches of 2-inch-thick structural steel compared to 5-1/2 and 10-1/2-pound charges specified by the SRI and U. S. Army formulas, respectively. For severing 18 linear inches of structural steel of 1- to 3-1/2-inch thicknesses, that formula prescribes Composition C-4 charges (or explosive of equal brisance) which contain from 1-1/2 to 3 times less explosive than charges specified by the SRI formula, and from 2 to 12-1/2 times less explosive than charges calculated by the U. S. Army formula. The economy of explosive realized through utilization of the modified formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ is significantly greater if again explosive charges prescribed by the three formulas for cutting the 14WF426 steel beam with 1-7/8-inch-thick web, 3-1/16-inch flanges, and 125.25-square-inch cross-sectional area of steel are compared. The SRI formula prescribes a 24.52-pound charge of C-4 explosive, and the U. S. Army formula specifies a 35.05-pound charge (Table IX), yet the formula just given prescribes a 15.27-pound charge computed on the basis of sliced C-4 explosive with a 1.57-gram per cubic centimeter density, which is normal. In seven test shots 11.75- to 13.27-pound C-4 explosive charges completely cut the large 14WF426 beam. Thus, by specifying a charge 2 inches

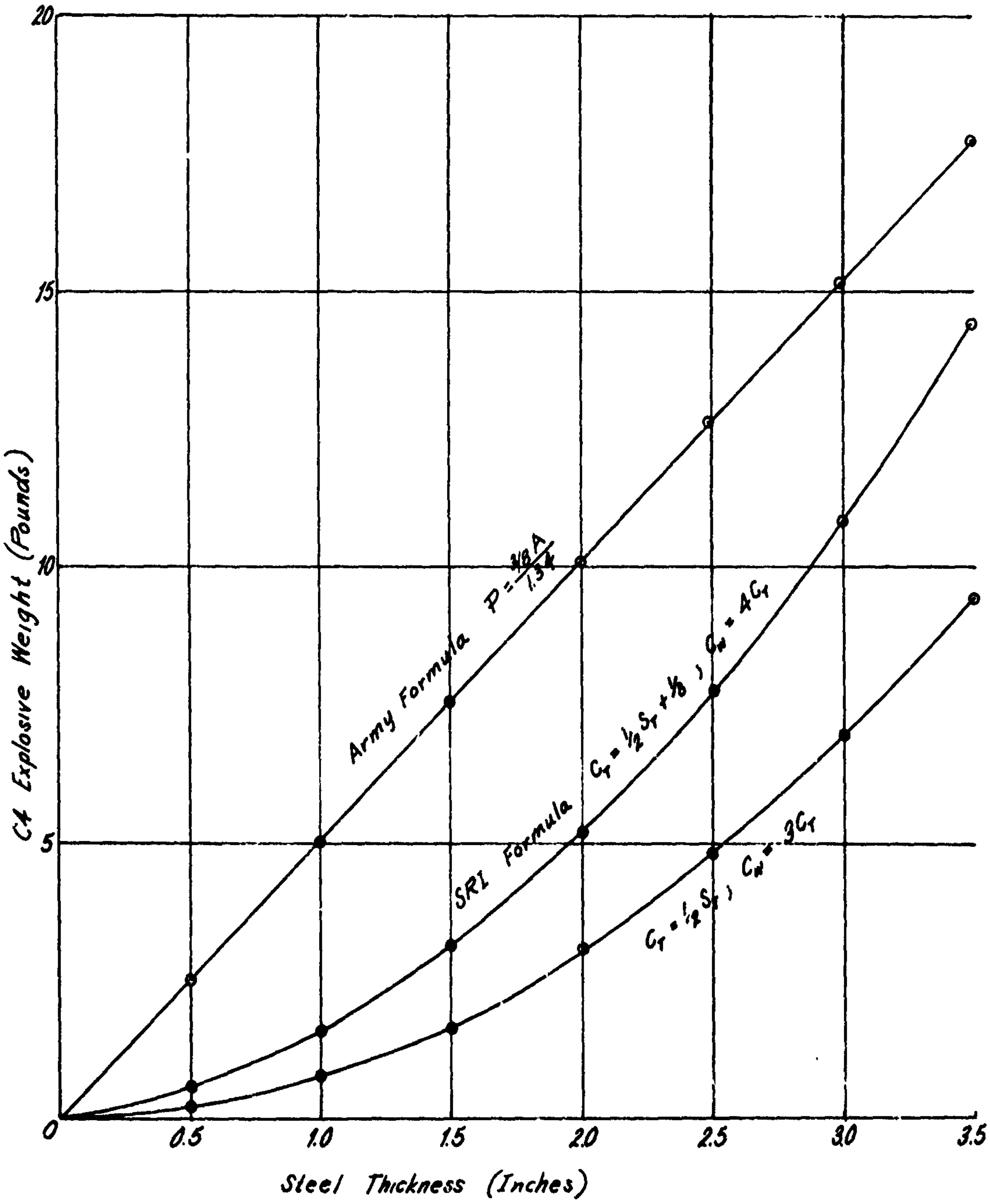

Fig. 63. Explosive weights calculated to cut 18 linear inches of steel by various formulas.

narrower and 1/8 inch thinner, the 3:1 ratio formula ($C_T = 1/2\ S_T$, $C_W = 3\ C_T$) achieves an explosive reduction of about 9-1/2 pounds over the SRI formula. In the application of both formulas, plastic or sheet explosive are required, and minimum thicknesses of 1/2 inch for C-4 explosive and 1/4 inch for Detasheet explosive are prescribed to prevent misfires from noninitiation of thin explosive charges.

(2) Optimum Positioning of Charges. An essential but not so critical element of explosive demolition of steel angles, channels, and plates, correct positioning of charges was found to be a highly significant factor that required exactness for reliable explosive cutting of wide-flange steel beams with linear contact charges. Single-explosive charges detonated at one point in close contact with the steel along the desired line of cut consistently severed steel angles, channels, and plates. But two to three charges, located at specific offsets on opposite sides of the steel beams and detonated precisely simultaneously at all priming points, were required for reliable demolition of wide-flange steel beams.

The offset between charges emplaced on opposite sides of steel beams was revealed to be critical. Excessive offset between charges such as the 1 inch recommended both by SRI and the U. S. Army yielded demolition failures because the fillets and often some of the flanges were uncut. At the other extreme, insufficient offset between charges on opposite sides of the beams produced demolition failures as the opposed charges, upon detonation, tended to neutralize one another and to compress the steel at the fillet of the beam without splitting it. The U. S. Army-recommended placement of two C-shaped charges at 1 inch offset on opposite sides of the beam, in addition to being highly susceptible to failures from excessive charge offset, was also vulnerable to inexact simultaneous initiation and nonuniform rates of detonation in the two separately primed charges; both of these defects caused demolition failure because one charge detonating ahead of the other set up a shock in the steel which removed the unexploded charge before initiation or before detonation was complete through all portions of the linear charges.

The criticality of offset between charges on opposite sides of a steel beam was manifested by demolition failures early in the tests; hence, experimentation was initiated to establish the optimum offset. Consideration of the mechanism of steel cutting with high explosive provided the understanding which led to fixing the limits of offset between charges on opposite sides of steel beams. As had already been seen, the longitudinal split, formed in the steel underneath the linear explosive charges, was the destructive mechanism of contact charges that severed steel beams. For the longitudinal split to form, spalling had to occur on the surface steel opposite the charge, and a free reflection surface on the steel opposite the charge was essential for formation of spall. As charges diametrically opposed did not have free reflection surfaces, spall could not form. Hence, the offset had to be great enough for the spall to form and tear free from the reflection surface steel. The width of the charge determined the width of the spall; therefore, the offset between charges was fixed by the charge width, which was related to the thickness of the steel. The thicker the steel, the wider the charge required to cut it, and consequently, the greater the offset distance needed between charges to permit spalling. The other extreme became evident when the longitudinal split formed in the steel along the center of the charge after spalling had occurred. If the offset was too great, except for excessive overcharges where shearing occurred, the longitudinal splits from charges on both sides of the beam did not connect to sever the beam. This defect usually occurred at the fillet of the beam, but it sometimes occurred on the flanges and the web also.

Application of the principles just described yielded reliable explosive demolition on both large and small wide-flange steel beams in 79 experimental firings. For explosive cutting of steel beams with linear contact charges emplaced and detonated simultaneously on both sides of the beams, the optimum offset between charges was the alignment of an edge of one charge opposite the center of the charge on the other side of the beam for steel thicknesses of less than 2 inches (Fig. 64). On beams with steel thicknesses of 2 inches or greater, the optimum offset was the alignment of the one charge opposite an edge of the charge on the other side of the beam (Fig. 65).

(3) Optimum Priming and Initiation. Successful explosive demolition of structural steel shapes, especially wide-flange beams, required the utilization of optimum priming methods for reliable initiation of charges at precise points. Faulty priming and inexact timing of charge initiation caused 32 of the 52 demolition failures that occurerd on steel plates and wide-flange steel beams (Appendix C). The requirements for priming and initiation of explosive charges were disclosed to be more critical and exacting for demolition of wide-flange beams than for cutting of steel plates; hence, details for each are presented separately.

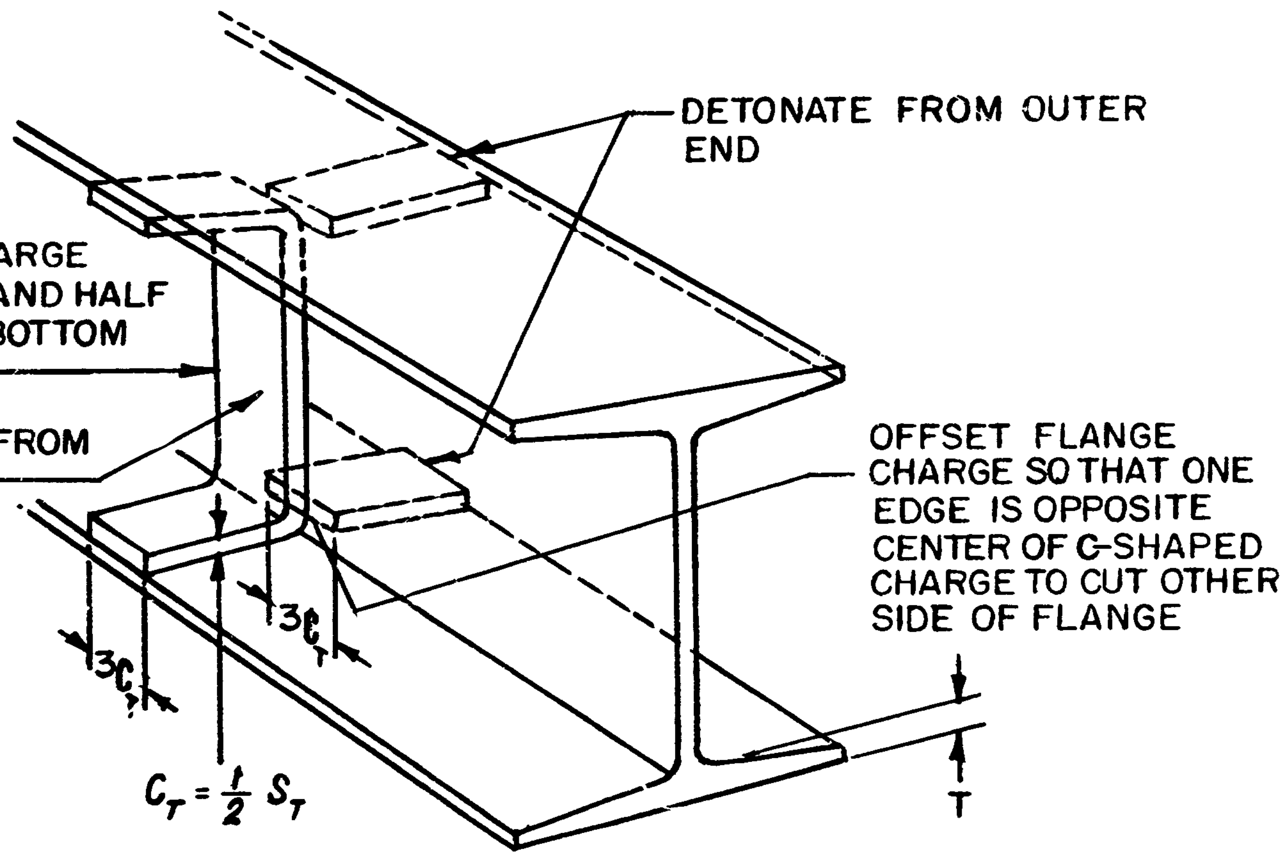

Fig. 64. Charge placement for explosive cutting of wide-flange beams with steel thicknesses of less than 2 inches.

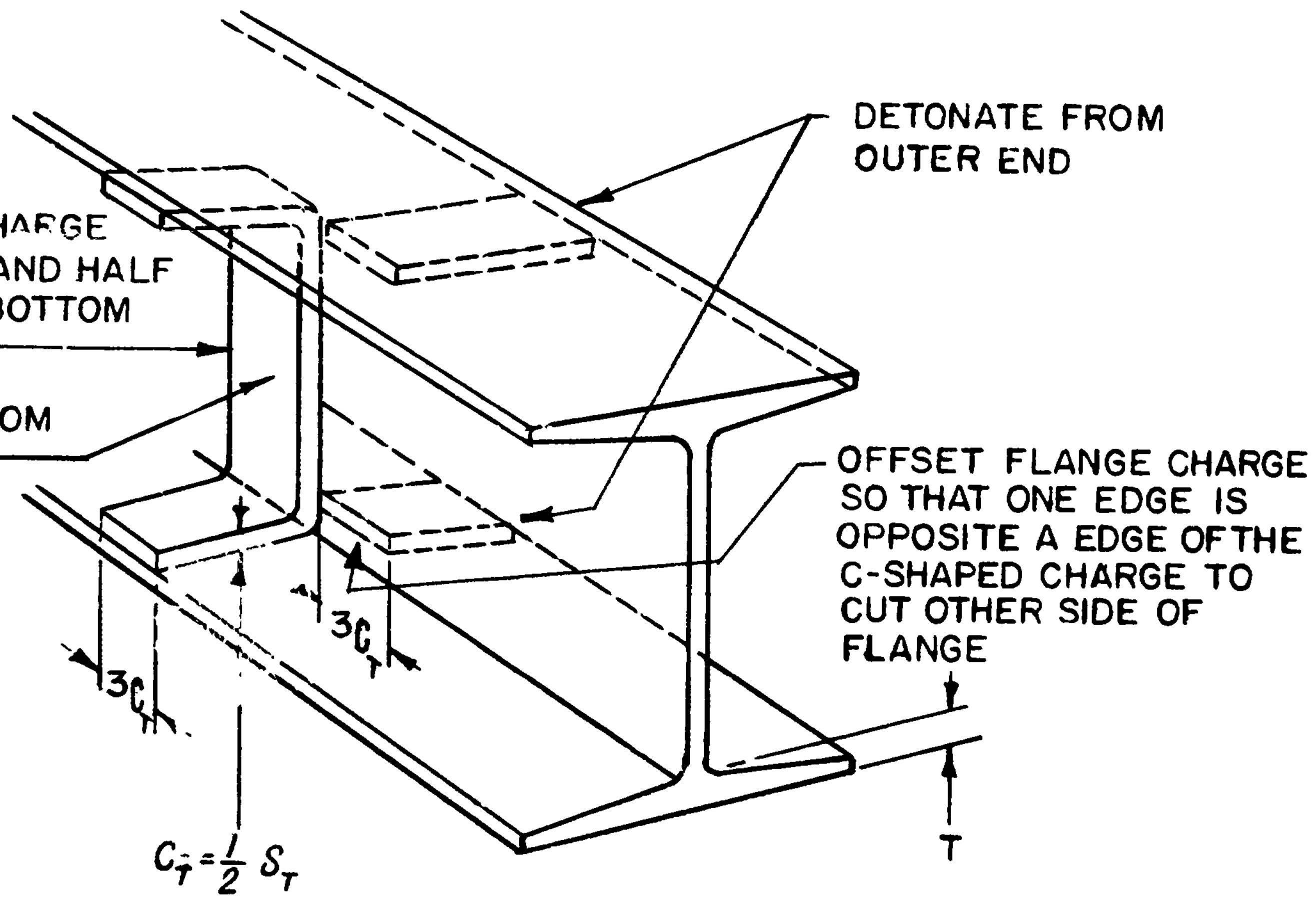

Fig. 65. Charge placement for explosive cutting of wide-flange beams with steel thicknesses of 2 inches or more.

The analyses of variance calculated on the charge yields of the factorial experiments (Appendix B) proved mathematically that the point of charge initiation had no significant effect on the shattering ability of steel-cutting explosive charges. But the results of explosive-cutting experiments on steel plates revealed that explosive charges should be at least 1/4 inch thick under the base end of the blasting cap at the point of initiation for effective demolition. Appendix C (test shots 185, 186, 189, 191, 318, 319, 320, 324, 336, 353 to 355, 368, and 379) shows that 14 demolition failures occurred on steel plates on which the steel was uncut directly under the points of initiation of the 1/4-inch-thick charges by blasting caps, which were slightly embedded in the explosive. Increasing the charge thickness so that 1/4 inch of explosive was between the base of the cap and the steel eliminated similar demolition failures in other test shots. All high-explosive charges, regardless of explosive type, require a minimum thickness of 1/4 inch of explosive beneath the base end of the blasting cap for the explosive shock to reach sufficient intensity that will insure satisfactory cutting or shattering effect (2) (3) (4). For that reason, to sever structural steel targets, Composition C-4 explosive charges should not be thinner than 1/2 inch at the point of initiation, and Detasheet explosive charges should not be less than 1/4 inch in thickness. Even though 1/4-inch-thick charges of C-4 explosive when detonated will reliably cut steel thicknesses of 1/2 inch or less, it is difficult and impractical to cut and emplace such thin C-4 charges. A more sensitive high explosive than Composition C-4, EL506A-5 Detasheet explosive of 1/4-inch thickness can be reliably detonated by a blasting cap with the base end butted against the explosive. A charge width of 1 inch is also considered the minimum feasible for operational demolitions, although the test results showed that narrower widths will cut steel thicknesses of 1/2 inch and less.

In 106 experimental firings that evaluated explosive techniques for demolition of wide-flange steel beams (Appendix C), defective priming and initiation of the explosive charges caused 18 of the 27 demolition failures in which steel beams were not completely cut. Causes of the other nine failures, which were excessively thin charges, incorrect charge offsets, and low-density explosives, have been discussed previously. The 18 demolition failures from defective charge priming and initiation were caused by lack of precise simultaneous detonation in the multiples of two to three explosive charges emplaced on the four half flanges and webs to cut the steel beams by explosive force from both sides. Four of five priming methods evaluated for simultaneous detonation of the multiple explosive charges yielded these 18 failures. Only one priming method, use of detonating cord priming assemblies, proved reliable. In Table X the five evaluated priming methods are described, and the position of the explosive charges on the beams and the points of initiation of the charges for each method are given; the test results and causes of demolition failures for each method are also listed.

In comparison of complete cuts versus incomplete cuts, the experimental data in Table X show that detonating cord priming assemblies were significantly more reliable than U. S. Army electric blasting caps in series circuits for simultaneous initiation of multiples of two to three explosive charges on steel beams. Priming method "b" which utilizes a three-strand detonating cord priming assembly initiated by a single electric cap, in 53 test shots, was 100 percent reliable in simultaneously detonating multiples of three explosive charges emplaced at three separate points on wide-flange steel beams. Designated priming method "c", a two-strand detonating cord priming assembly simultaneously exploded multiples of two explosive charges separated on opposite sides of steel beams, and complete cuts were produced in 17 of 19 test firings. With the two incomplete cuts, lack of simultaneous detonation between the two continuous charges, slightly offset longitudinally on opposite sides of the beam, was thought to have resulted from possible use of nonuniform lengths of the two detonating cord strands that formed the priming assemblies. Nevertheless, detonating cord priming assemblies achieved simultaneous detonation in multiples of two or three explosive charges in 70 of 72 steel-cutting tests on wide-flange steel beams. By comparison, U. S. Army electric caps in two- to three-cap series circuits fired by current from U. S. Standard 10-cap blasting machines achieved simultaneous detonation of like multiples of steel-cutting charges in only 18 of 34 test shots; lack of simultaneous detonation in the multiple explosive charges resulted from variations in the times of initiation of the electric blasting caps used to initiate the charges.

Times of initiation of electric blasting caps vary because a short but measurable period of time is required for the electricity to generate sufficient heat in the bridge wire that ignites the flash compound of the cap. This period of time, which depends upon the amount of current flowing through the bridge, is in the order of magnitude of thousandths of seconds. Because all electric blasting caps cannot be made to have their firing characteristics exactly the same, the times of firing vary slightly from cap to cap, even though the current supplied is held constant (22). U. S. Army electric caps

Table X. Significance of Priming Methods in Explosive Demolition of Steel Beams

No. of Charges and Their Positions on Steel Beams	Description of Priming Assembly and Points of Initiation of Charges	No of Test Shots	Complete Cuts	Incomplete Cuts	Primary Cause of Demolition Failure
Three explosive charges that consisted of a continuous charge on half flanges and web on one side of beam, and two half-flange charges on other side, one on each half flange. Designated method "b" in par. 8b.	Detonating cord priming assembly of three equal lengths of detonating cord with either knots or J-1 caps at one end and J-2 cap that connected other end for simultaneous initiation. Center priming of continuous charge and end priming of half-flange charges.	53	46	7 But none caused by defective priming or initiation	Insufficient explosive in excessively thin charges in six test shots, low-density C-4 explosive in other test. All charges detonated simultaneously in all 53 test shots.
Two explosive charges continuous over half flanges and web on both sides of beam with charges offset as shown in Figs. 64 and 65. Designated method "e" in par. 8b.	Detonating cord priming assembly of two equal lengths of detonating cord with either knots or J-1 caps at one end and J-2 cap that connected other ends for simultaneous initiation. Center priming of both continuous charges.	19	17	2	Lack of simultaneous detonation of two charges apparently caused by nonuniform lengths of detonating cord in priming assemblies or nonuniform rates of detonation in the paste explosive charges (test shots 63 and 65).
Two continuous charges emplaced as described directly above. Charge offset 1 inch as shown in Fig. 23. Designated method "d" in par. 8b.	Two U.S. Army special electric caps in series firing circuit, primed center of two continuous charges.	21	12	9	Excessive charge offset caused one failure, other eight failures resulted from lack of simultaneous detonation caused by variation in times of initiation of two electric blasting caps.
Three charges that consisted of a continuous charge on half flanges and web on one side of beam and two half-flange charges on other side, one on each half flange. Charges offset as shown in Figs. 64 and 65. Designated method "c" in par. 8b.	Three U. S. Army special electric caps in series firing circuit, primed center of continuous charge and ends of half-flange charges.	3	1	2	Lack of simultaneous detonation of two charges caused by variations in times of initiation of three electric blasting caps
Three charges that consisted of a continuous charge on half flanges and web on one side of beam and two half-flange charges on other side, one on each half flange. Charges offset 1 inch as shown in Fig. 21. Designated method "a" in par. 8b.	Three U. S Army special electric caps primed ends of two half-flange charges and end of continuous charge.	10	3	7	Excessive charge offset caused one failure, other six failures resulted from lack of simultaneous detonation of two charges produced by variations in times of initiation of three electric blasting caps

manufactured to tolerances of plus or minus 5 milliseconds could have variations of as much as 10 milliseconds between times of initiation of two or more caps in a series circuit (21).

With a detonation rate of about 21,000 feet per second (3), detonating cord permits closer control in the time of initiation of multiple explosive charges than is possible with electric caps. For example, a 1-inch difference in lengths of strands in a detonating cord priming assembly would cause a variation in charge initiation time of only about 1/252 thousandths of a second (21,000 feet per second x 12 inches = 252,000-inch-per-second rate of detonation) compared to a possible variation of up to ten thousandths with electric caps.

Explosive cutting of wide-flange steel beams by contact charges, then, required the combined destructive effect of at least two explosive charges detonated simultaneously on the half flanges and web of both sides of the beams. When the charges, whether two or three, were not initiated simultaneously so that detonation occurred uniformly in all charges, one shock wave apparently propagated through the steel ahead of the other shock waves and displaced all or portions of the unexploded or later exploding charges before detonation had occurred or was completed. Because the allowable time variation for simultaneous detonation to occur in separately primed explosive charges emplaced at different points on steel is in the microsecond range, charge initiation by priming assemblies of detonating cord with its detonating velocity of 21,000 feet per second yielded more precise timing of the charge detonations than the U. S. Army electric caps with initiation time variations in the millisecond range (10). Moreover, with C-shaped explosive charges continuous over the web and half flanges, center point initiation achieved simultaneous detonation with a greater degree of reliability than end initiation where detonation progressed through the explosive in only one direction over twice the linear distance.

c. Tests on Steel Bars. Explosive cutting of round and square steel bars primarily evaluated the cross-fracture charge and diamond charge demolition techniques although nine test firings employed offset charges detonated on both sides of steel bars to shear them, which is considered an outmoded steel-cutting method. For evaluation of the cross-fracture charge technique, both rectangular and triangular (referred to as saddle charges) shaped explosive charges were detonated at one end in direct contact along one side of steel bars to break them by cross fractures formed in the steel at free ends of the charges. The diamond charge technique was employed to investigate the steel-cutting effectiveness of diamond-shaped explosive charges that utilized the reinforced effect of colliding stress waves to cut steel bars by tensile fractures induced in the steel near the center of the diamond at the collision point of two explosive shock waves. Thus, the 81 complete cuts on both round and square steel bars, which are described in detail in Appendix C, are considered in this discussion. Table XI contains a comparison of the steel-cutting effectiveness between the cross-fracture and diamond charge demolition techniques based on those 81 complete cuts.

Experimental data in Table IX illustrate the superiority of the diamond charge demolition technique over the cross-fracture charge technique in producing maximum destructive effect with minimum expenditure of explosive. For demolition of steel bars having similar thicknesses and cross-sectional areas, cross-fracture charges expended from 2 to 7 times more explosive than diamond-shaped charges which had to be only 1/4 inch thick for severing up to 6-inch-thick steel bars. Conversely, to cut steel bars of similar thicknesses, rectangular cross-fracture charges had to be at least 1 inch thick, and the longer triangular cross-fracture charges had to be a minimum of 2/3 inch thick. For compl[illegible] cross-fracture charges show a relationship of explosive expendi[illegible] to area of steel cut of P = 1/11 A (minimum) to P = 1/3 A (maximum) compared to a cutting relationship of P = 1/7 A (maximum) to P = 1/32 A (minimum) for diamond charges (where P = pounds of C-4, Detasheet, or paste explosive, and A = cross-sectional area of the steel in square inches). However, in the evaluation of the two explosive demolition techniques, the true significance of the superiority of the diamond-shaped charge becomes more apparent if for the comparison only the minimum size charges listed in Table XI are considered for each type of charge. For example, no great difference in explosive weights exists between the maximum and the minimum size cross-fracture charges used to sever steel bars. But a highly significant difference exists between the explosive weights of maximum size diamond-shaped charges and the minimum size ones. The explosive weights of the minimum size diamond-shaped charges, in addition, represent a more exact explosive requirement for effective demolition by the diamond charge technique because the majority of complete cuts were achieved with charges weighing at or near those minimum amounts. As shown in Appendix C, 8 of the 9 complete cuts on steel bars, 6 inches in diameter, were obtained with diamond-shaped charges of 0.90 to 1.49 pounds of explosive; the other charge contained 2.36 pounds of C-4 explosive, which was an overcharge. Test results for cutting steel bars, 4 inches in diameter, with diamond-shaped charges show a similar relationship. Six of the eight complete cuts

Table XI. Comparative Effects of Explosive Techniques Used to Cut Steel Bars

Steel Bar Shape	Steel Bar Thickness of Diameter (in.)	Area (sq in.)	Charge Computed by Army Formula (a)(b)	Characteristic of Actual Charge Used for Complete Cut: Cross-Fracture Charge Technique(b)					Diamond-Shaped Charge Technique				
				Maximum Size Charge		Minimum Size Charge		No. of Complete Cuts	Maximum Size Charge		Minimum Size Charge		No. of Complete Cuts
				Explosive Weight (lb)	Relation of Experimental Weight to Steel Area	Explosive Weight (lb)	Relation of Experimental Weight to Steel Area		Explosive Weight (lb)	Relation of Experimental Weight to Steel Area	Explosive Weight (lb)	Relation of Experimental Weight to Steel Area	
2-Inch Square	2	4.00	1.12	0.98	P = 1/4 A	0.55	P = [illegible]/7 A	16	No	Test	Firings		
4-Inch Square	4	16.00	4.48	2.24	P = 1/7 A	1.10	P = 1/14 A	5	[illegible].23	P = 1/7 A	0.75	P = 1/20 A	10
2-Inch Round	2	3.14	2.98	0.41	P = 1/7 A	0.41	P = 1/7 A	5	0.42	P = 1/7 A	[illegible].13	P = 1/20 A	5
3-Inch Round	3	7.07	1.98	1.85	P = 1/3 A	1.85	P = 1/3 A	1	0.87	P = 1/8 A	0.26	P = 1/27 A	7
4-Inch Round	4	12.57	3.52	3.08	P = 1/4 A	1.10	P = 1/11 A	10	1.43	P = 1/[illegible] A	0.42	P = 1/30 A	8
6-Inch Round	6	28.27	7.91	3.78	P = 1/7 A	3.66	P = 1/7 A	5	2.36	P = 1/12 A	0.90	P = 1/32 A	9

(a) Formula, $P = \frac{3/8\ A}{1.34}$ was used for computation of charges on square steel bars and round steel bars with diameters of 2 inches or more. Formula $P = \frac{D^2}{1.34}$ was used to calculate charges for round steel bars with diameters of 2 inches.

(b) Summarized data do not include test results on 18-inch round steel bars as those results were considered biased. (Results of test shot 155 of Appendix C were not included because steel bar was intentionally overcharged.)

on steel bars 4 inches in diameter were made with diamond-shaped charges of 0.42- to 0.57-pound explosive weight.

Demolition results of the 155 explosive-cutting tests on steel bars (Appendix C) also disclosed that cross-fracture and diamond-shaped charges must have certain minimum dimensions for maximum reliability in cutting different types of steel in given thicknesses. Rectangular cross-fracture charges should have lengths equal to about 2-1/2 to 3 times this diameter or thicknesses of the steel bars being cut, widths equal to about 1/2 the diameter of round bars or widths equal to the thickness of square bars, and a minimum thickness of 1 inch. Cross-fracture charges of triangular shapes (saddle charges), which are longer than rectangular ones, may have minimum thicknesses of 2/3 inches for cutting mild steel bars of 6-inch diameters or less; each charge should have a 1-inch minimum thickness for cutting alloy-steel bars of similar diameters; they must have bases (widths) equal to 1/2 the circumference of round bars or the thicknesses of square bars, and the altitudes (lengths) of these charges shaped as isoceles triangles must be two times the base. Because they must completely encircle the steel bars so that the points of the long axes of the charges meet, diamond-shaped charges must have long axes equal to the circumferences of round steel bars or the perimeters of square steel bars (add about 1/2 to 1 inch to the perimeters of square bars to compensate for the 90-degree bends at the four corners). The short axes of diamond-shaped charges must be equal to 1/2 of the long axes, and their thickness must be a minimum of 1/4 inch for Detasheet explosive charges and 1/2 inch for C-4 charges to cut mild steel bars of thicknesses of 6 inches or less. Diamond-shaped charges must be at least 1/2 inch thick for cutting up to 6-inch-thick alloy steel bars with lengths exceeding 18 inches. Because 2/3-inch-thick diamond-shaped charges failed to sever 6-inch-diameter alloy steel bars of 18-inch lengths, 1 inch or the thicker charges are required. The test results also indicated that the use of explosive charge weights specified by the U. S. Army formulas is necessary for reliable cutting of short steel bars where the proximity of the free end of the bars to the free end of the charges can cause demolition failures through the reflected shock wave effect from the end boundaries.

As an explosive charge of finite length is required to break a steel bar by a major cross fracture, so also is a finite length of bar steel necessary for the formation of the cross fracture or end split produced by the spall surface tension shock wave colliding with the charge surface rarefaction wave (as stated in paragraph 3, "Mechanism of Steel Cutting with Explosives"). In describing the mechanism of the end split or cross fracture, William E. Drummond of SRI showed that explosive shock produces a local tension maximum in steel at the point where the tension wave from the bottom surface and the rarefaction front from the top surface meet; if this tension exceeds the breaking strength, the steel splits at that point (8). The end split is said to start in the interior of the steel and propogate both ways. Because explosive shock is known to travel through steel at the velocity of sound, a finite length of steel is necessary for the traveling shock waves to reflect, collide, and reach the maximum intensity required to produce the cross-fracture split. Hence, with end-primed explosive charges of 5- to 13-inch lengths placed and detonated along the center of the 18-inch round steel bars, the author believes that there was insufficient steel beyond the free ends of the charges for the shock waves to reflect and collide with maximum intensity to produce the cross-fracture split. The ends of the steel bars being so close to the ends of the charges no doubt dissipated the explosive energy through the reflected influence of the additional end boundary.

Twelve explosive-cutting experiments on 4-inch square steel bars (Appendix C), moreover, proved that the diamond charge steel-cutting technique was equally as effective on square steel bars as on round ones although the current U S. Army demolition manual and the SRI report announcing its development both specify its employment for cutting round steel bars only. In 10 experimental firings, diamond-shaped charges completely cut ten 4-inch square steel bars when the long axes of the diamond completely encircled the perimeters of the bars, and the short axes were equal to one-half the lengths of the long axes. Use of such charges that did not completely encircle the perimeters of the 4-inch square steel bars caused the two incomplete cuts.

Adaptation of the diamond charge technique to cutting square steel bars required only that the long axes of the charges be lengthened enough to bend around the four 90-degree corners of the square bars and still completely encircle the bars with close contact between explosive and steel, especially at the corners. Thus, with the forthcoming availability of sheet explosive in the recently standardized M118 demolition charge, user troops can easily and quickly employ diamond-shaped charges for stress wave cutting of steel bars, shafts, or any other irregular solid steel shape. Stress wave cutting of steel bars is a more effective explosive demolition method than cutting by either the cross-fracture or the dual-offset charge techniques.

IV. CONCLUSIONS

16. Conclusions. It is concluded that:

a. Both charge width and charge thickness have significant effects on the steel-cutting efficiency of contact explosive charges.

b. The point of charge initiation does not significantly affect the shattering power of contact explosive charges on steel.

c. A 3:1 ratio of charge width to charge thickness is optimum for contact explosive charges calculated to cut structural steel in thicknesses of 3 inches or less.

d. The formula $C_T = 1/2\ S_T$, $C_W = 3\ C_T$ is more accurate and efficient than the U. S. Army formula $P = \frac{3/8\ A}{1.34}$ for calculation of contact charges of Composition C-4, paste, and EL506A-5 Detasheet explosives to cut structural steel.

e. Composition C-4, paste, and EL506A-5 Detasheet explosives are equally effective as contact charges for cutting structural steel; because of its variable density, paste explosive is less effective than Composition C-4 explosive for cutting round steel bars.

f. The optimum offsets between linear contact charges emplaced to cut from both sides, for reliable explosive demolition of steel beams, are the alignment of the edge of one charge opposite the center of the charge on the other side of beams with steel thicknesses of less than 2 inches, and the alignment of the edge of one charge opposite the edge of the charge on the other side of beams with steel thicknesses of 2 inches or more.

g. The detonating cord firing system is more reliable than electric blasting caps in series circuits for simultaneous detonation of multiple contact charges used in the explosive demolition of steel beams.

h. The diamond charge technique is more effective and dependable than either the cross-fracture or the dual-offset charge technique for explosive cutting of steel bars.

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APPENDIX A

AUTHORITY

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24. (U) Objective of Task: Develop advanced demolition techniques for explosive materials, blasting accessories and other applicable materials for controlled destruction of military targets; barrier creation and reduction, and construction operations, evaluate the military use of technological improvements in foreign and commercial explosives, blasting procedures; and providing consultant services in the field of demolitions to our field forces and other agencies. To advance the techniques for tactical employment of ADM's.

25.(U) Plans for FY 66: Provide consultant services in the field of demolitions. Evaluate proposals, suggestions and patents, technically review manuals and other publications. With our field forces,to determine the most critical problem areas, conduct studies and design for experimental charges or materials for field application on specific target types indicated by field forces. Prepare interim reports, development programs and other duties required to meet the objectives and provide technical information for task NEW.

26.(U) Plans for Subsequent Years: Changing military tactics, targets, materiel and demolition requirements dictate an alert and aggressive program be maintained, not only to cope with these changes but to advance beyond our present position, which in some instances is pre-World War II. This task is planned to accomplish the above.

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APPENDIX B

STATISTICAL ANALYSES OF STEEL-CUTTING EXPERIMENTS

by

Richard E. Deighton

Data from four factorial experiments in which new techniques for explosive demolition of structural steel plates were analyzed in connection with the examination of current U. S. Army methods of steel cutting with high-explosive charges.

Experiment 1

This complete factorial experiment with three of the four factors at two levels and the fourth factor at three levels had two replicates. The factors considered and their levels were as follows:

Types of Explosive

Level 1: Composition C-4
Level 2: Paste

Thickness of Charge

Level 1: 1/2 inch
Level 2: 1 inch

Point of Charge Initiation

Level 1: Center
Level 2: End

Width of Charge

Level 1: 3/4 inch
Level 2: 1-3/8 inches
Level 3: 2 inches

Table XII gives the analysis of variance for experiment 1 for explosive test results on steel plates. The analysis revealed that the types of explosives, the thicknesses of the charges, and the widths of the charges were significant. Note that the points of initiation of the charges were not significant. The interaction between widths of charges and thicknesses were also highly significant. Moreover, the interaction among widths of charges, thicknesses of charges and types of explosives were significant. The fact that these interactions were significant is plausible because the main effects of these same factors were highly significant.

Table XII. Analysis of Variance for Experiment 1 for Explosive Test Results on Steel Plates

Effect	Calculated F Value	Tabular F Value		
		Degree of Freedom	95%	99%
W	$\frac{9132.05}{24.40} = 374.26^{(2)}$	2 and 24	3.42	5.67
I	$\frac{22.55}{24.40} = 0.92$	1 and 24	4.28	7.88
T	$\frac{4850.13}{24.40} = 198.78^{(2)}$	1 and 24	4.28	7.88
E	$\frac{380.25}{24.40} = 15.58^{(2)}$	1 and 24	4.28	7.88
WI	$\frac{2.16}{24.40} = 0.09$	2 and 24	3.42	5.67
WT	$\frac{1527.77}{24.40} = 62.61^{(2)}$	2 and 24	3.42	5.67
WE	$\frac{26.22}{24.40} = 1.07$	2 and 24	3.42	5.67
IT	$\frac{1.96}{24.40} = 0.08$	1 and 24	4.28	7.88
IE	$\frac{6.09}{24.40} = 0.25$	1 and 24	4.28	7.88

Table XII (cont'd)

Effect	Calculated F Value		Tabular F Value		
			Degree of Freedom	95%	99%
TE	$\frac{22.01}{24.40}$ =	0.90	1 and 24	4.28	7.88
WIT	$\frac{26.08}{24.40}$ =	1.07	2 and 24	3.42	5.67
WIE	$\frac{3.01}{24.40}$ =	0.12	2 and 24	3.42	5.67
WTE	$\frac{96.48}{24.40}$ =	3.95 (1)	2 and 24	3.42	5.67
ITE	$\frac{3.15}{24.40}$ =	0.13	1 and 24	4.28	7.88
WITE	$\frac{4.63}{24.40}$ =	0.19	2 and 24	3.42	5.67

Notes: W = Width of charge.
I = Point of initiation.
T = Thickness of charge.
E = Type of explosive.

(1) Significant.
(2) Highly significant.

Experiment 2

This experiment consisted of only one factor, namely, explosive charge width. Five different widths were tested with three replicates of each width, as follows: Level 1 = 1 inch; level 2 = 1-1/4 inches; level 3 = 1-1/2 inches; level 4 = 1-3/4 inches; and level 5 = 2 inches. The effect (W) was 12.3 for the calculated F value. This denotes significance at the 5 percent level. The numerator and the denominator degrees of freedom were 4 and 10, respectively. The actual F value in the 95-percent range was 3.48. These data indicate that explosive charge width is of significance. As there are more than two levels of width, Tukey's method of simultaneous confidence intervals must be applied in order to determine which pairs of widths are different in significance and effect.

Table XIII gives the results of the application of Tukey's method to the data obtained. If the value of zero is not included between the lower confidence limit and the upper confidence limit, it can be said that a significant difference exists between the explosive charge widths being considered. This table shows that the 1-inch width differs significantly from the 1-1/2-, the 1-3/4-, and the 2-inch widths. Also, the 1-1/4-inch width differs significantly from the 1-3/4-inch and the 2-inch widths. No other significant differences were found.

Table XIII. Tukey's Method of Simultaneous Confidence Intervals for Experiment 2

Explosive Charge Width	Lower Confidence Limit (1)	Upper Confidence Limit (1)
1. 1 in. and 1-1/4 in.	-8.0	+3.0
2. 1 in. and 1-1/2 in.	-11.3	-0.3*
3. 1 in. and 1-3/4 in.	-14.7	-3.8*
4. 1 in. and 2 in.	-15.0	-4.0*
5. 1-1/4 in. and 1-1/2 in.	-8.8	+2.2
6. 1-1/4 in. and 1-3/4 in.	-12.2	-1.2*
7. 1-1/4 in. and 2 in.	-12.5	-1.5*
8. 1-1/2 in. and 1-3/4 in.	-8.9	+2.1
9. 1-1/2 in. and 2 in.	-9.2	+1.8
10. 1-3/4 in. and 2 in.	-5.8	+5.2

Note: These limits were calculated using a 95 percent studentized range value of 4.65.

* Denotes significance at the 5 percent level.

Experiment 3

This experiment consists of two factors and two levels of each factor. The experiment has three replicates. The factors and their levels are given in Table XIV, which presents the analysis of variance for this experiment. The analysis reveals that explosive charge widths are significant, but the types of explosives are not significant.

Table XIV. Analysis of Variance for Experiment 3

Effect*	Calculated F Value	Actual F Value (95% range)
E	5.22	5.32
W	67.39**	5.32
EW	2.17	5.32

Note: Numerator and denominator degrees of freedom were 1 and 8, respectively, for all effects.

* Factor E, Type of explosive:
Level 1 = Paste alone
Level 2 = Paste with aluminum powder

Factor W, Explosive charge width:
Level 1 = 1 inch
Level 2 = 2 inch

** Denotes significance at the 5 percent level.

Experiment 4

This experiment consists of two factors and two levels of each factor. The experiment has three replicates. The factors and their levels are given in Table XV which presents the analysis of variance. The analysis showed that explosive charge widths are significant, but the method of initiation is not significant.

Table XV. Analysis of Variance for Experiment 4

Effect*	Calculated F Value	Actual F Value (95% range)
I	0.03	5.32
W	35.13**	5.32
IW	0.15	5.32

Note: Numerator and denominator degrees of freedom were 1 and 8, respectively, for all effects.

* Factor I, Method of initiation:
Level 1 = End priming
Level 2 = Center priming

Factor W, Explosive charge width:
Level 1 = 1 inch
Level 2 = 2 inch

** Denotes significance at the 5-percent level.

APPENDIX C

SUMMARY OF TEST DATA

Table XVI. Summary of Explosive-Cutting Test Results on Steel Plates

Test Shot	Plate Dimension (in.)			Explosive Charge							Results
	Length	Thickness	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\,A}{1.34}$	Weight (lb) Actual	Percentage of P=3/8A to Actual	Kind of Explosive	Dimension (in.) Width	Dimension (in.) Thickness	Dimension (in.) Length	
1	6	1	6.00	1.68	0.59	35.11	Paste	2-3/4	5/8	6 *	Complete cut.
2	10-1/2	1	10.50	2.93	0.95	32.42	Paste	2-1/2	3/4	10-1/2	Complete cut.
3	10-1/4	1	10.25	2.87	0.41	14.28	Paste	1	5/8	10-1/4	Incomplete cut.
4	10-1/2	1	10.50	2.93	0.72	24.57	Paste	2-1/2	5/8	10-1/2*	Complete cut.
20	6	1	6.00	1.68	0.27	16.07	Paste	1-3/4	9/16	6 *	Complete cut
21	6	1	6.00	1.68	0.36	21.42	Paste	2-1/2	7/8	6 *	Complete cut.
22	6	1	6.00	1.68	0.37	22.02	Paste	2-1/2	11/16	6 *	Complete cut.
23	6	1	6.00	1.68	0.34	20.23	Paste	1-3/4	5/8	6 *	Incomplete cut.
24	6	1	6.00	1.68	0.28	16.66	Paste	1-5/8	11/16	6 *	Complete cut.
25	6	1	6.00	1.68	0.27	16.07	Paste	1-11/16	5/8	6 *	Complete cut.
29	4-3/4	9/16	3.56	0.99	0.41	41.41	Paste	1-1/4	13/16	4-3/4	Complete cut.
30	4-3/4	9/16	3.56	0.99	0.41	41.41	Paste	1-1/2	13/16	4-3/4	Complete cut
181	12	1	12.00	3.35	0.50	14.92	Paste	1	3/4	12	Incomplete cut.
182	12	1	12.00	3.35	0.66	19.70	Paste	2	1/2	12	Incomplete cut.
183	12	1	12.00	3.35	0.96	29.25	Paste	2	5/8	12	Incomplete cut.
184	12	1	12.00	3.35	0.98	29.25	Paste	1-1/2	1	12	Incomplete cut.
185	12	1	12.00	3.35	1.11	33.13	Paste	2	15/16	12	Incomplete cut, 4-inch cut on plate end opposite initiation
186	12	1	12.00	3.35	1.11	33.13	Paste	2	15/16	12 *	Incomplete cut; 4-inch crack at both ends of plate.
187	12	1	12.00	3.35	1.11	33.13	Paste	3	5/8	12 *	Incomplete cut.
188	12	1	12.00	3.35	1.54	45.97	Paste	2	1-1/8	12	Complete cut
189	12	1	12.00	3.35	1.32	39.40	Paste	2	1-1/16	12	Incomplete cut; 8-inch cut at end opposite initiation.

Table XVI (cont'd)

Test Shot	Plate Dimension (in.)			Explosive Charge							Results
	Length	Thickness	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\,A}{1.34}$	Weight (lb) Actual	Percentage of P = 3/8 A to Actual	Kind of Explosive	Dimension (in.) Width	Dimension (in.) Thickness	Dimension (in.) Length	
190	1?	1	12.00	3.35	1.43	42.68	Paste	2	1-1/16	12	Complete cut; close to borderline.
191	12	1	12.00	3.35	1.43	42.68	Paste	2	1-1/16	12	Incomplete cut; cut 8 inches of end of plate away f[illegible] n initiation point.
:61	12	1	12.00	3.35	1.37	40.89	Paste	2	1-1/16	12	Complete cut.
310	12	1	12.00	3.35	1.48	44.17	Paste	2	1-1/16	12	Complete cut.
311	12	1	12.00	3.35	1.54	45.97	Paste	2	1-1/8	12	Complete cut
314	12	1	12.00	3.35	1.37	40.89	C-4	2	1	12	Complete cut.
315	12	1	12.00	3.35	1.37	40.89	C-4	2	1	12	Complete cut.
316	12	3/4	9.00	2.52	1.05	41.66	C-4	1-1/2	1	12	Complete cut.
317	12	3/4	9.00	2.52	0.72	28.57	C-4	1-1/4	3/4	12	Complete cut.
318	12	3/4	9.00	2.52	0.98	38.88	Paste	1-1/2	7/8	12	Incomplete cut; cut only 7 inches on end of plate away from point of charge initiation.
319	12	3/4	9.00	2.52	1.11	44.04	Paste	1-1/2	1-1/8	12	Incomplete cut; cut all of plate except 2 inches directly under point of charge initiation.
320	12	3/4	9.00	2.52	1.32	52.38	Paste	1-3/4	1-1/8	12	Same as test shot 319.
321	12	3/4	9.00	2.52	1.54	61.11	Paste	2	1-1/16	12	Complete cut
322	12	3/4	9.00	2.52	1.43	56.74	Paste	2	1-1/16	12	Complete cut.
323	12	3/4	9.00	2.52	1.32	52.38	Paste	2	1	12	Complete cut.
324	12	1/2	6.00	1.68	0.98	58.33	Paste	2	3/4	12	Cut plate except for 1½ inches at end of point of initiation.

Table XVI (cont'd)

Test Shot	Plate Dimension (in.)			Explosive Charge							Results
				Weight (lb)				Dimension (in.)			
	Length	Thickness	Cross-Sectional Area (in.)^2	Calculated $P = \frac{3/8\,A}{1.34}$	Actual	Percentage of P = 3/8A to Actual	Kind of Explosive	Width	Thickness	Length	
325	12	1/2	6.00	1.68	1.11	66.07	Paste	2	13/16	12	Complete cut.
326	12	1/2	6.00	1.68	1.05	62.50	Paste	2	3/4	12	Complete cut
327	12	1/2	6.00	1.68	0.98	58.33	Paste	3	5/8	12	Complete cut.
328	12	1/2	6.00	1.68	0.66	39.28	Paste	3	3/8	12	Incomplete cut
329	12	1/2	6.00	1/68	0.82	48.80	Paste	3	5/16	12	Incomplete cut.
330	12	1/2	6.00	1.68	0.66	39.28	C-4	1	13/16	12	Complete cut.
331	12	1/2	6.00	1.68	0.55	32.73	C-4	1	3/4	12	Complete cut
332	12	1/2	6.00	1.68	0.44	26.19	C-4	1	11/16	12	Cut all of plate except for 1 inch at plate end of point of initiation.
333	12	1/4	3.00	0.84	0.44	52.38	Paste	2	3/8	12	Complete cut.
334	12	1/4	3.00	0.84	0.44	52.38	Paste	2	3/8	12	Complete cut.
335	12	1/4	3.00	0.84	0.34	40.47	C-4	1	1/2	12	Complete cut
336	12	1/4	3.00	0.84	0.17	20.23	C-4	1/2	1/2	12	Cut plate except for 1 inch at plate end of point of initiation.
339	18	1	18.00	5.05	0.75	14.87	EL506A-5	1-1/2	1/2	18 *	Complete cut.
340	18	1	18.00	5.05	0.76	15.04	EL506A-5	1-1/2	1/2	18 *	Complete cut.
341	18	1	18.00	5.05	0.86	17.02	C-4	1-1/2	1/2	18 *	Complete cut.
342	18	1	18.00	5.05	0.84	16.63	C-4	1-1/2	1/2	18 *	Complete cut.
343	18	1	18.00	5.05	0.75	14.87	EL506A-5	1-1/2	1/2	18 *	Complete cut.
344	18	1	18.00	5.05	0.75	14.87	EL506A-5	1-1/2	1/2	18 *	Complete cut.
345	18	1	18.00	5.05	0.78	15.44	C-4	1-1/2	1/2	18 *	Complete cut
346	18	1	18.00	5.05	0.84	16.63	C-4	1-1/2	1/2	18 *	Complete cut.
347	18	1	18.00	5.05	0.78	15.44	C-4	1-1/2	1/2	18 *	Complete cut.
348	18	1	18.00	5.05	0.76	15.04	EL506A-5	1-1/2	1/2	18 *	Complete cut

Table XVI (cont'd)

Test Shot	Plate Dimension (in.)			Explosive Charge							Results
				Weight (lb)				Dimension (in.)			
	Length	Thickness	Cross-Sectional Area $(in.)^2$	Calculated $P = \frac{3/8\ A}{1.34}$	Actual	Percentage of P = 3/8 A to Actual	Kind of Explosive	Width	Thickness	Length	
350	18	1/2	9.00	2.52	0.21	08.33	EL506A-5	3/4	1/4	18 *	Complete cut.
351	18	1/2	9.00	2.52	0.23	09.12	EL506A-5	3/4	1/4	18 *	Complete cut.
352	18	1/2	9.00	2.52	0.21	08.33	EL506A-5	3/4	1/4	18 *	Complete cut.
353	18	1/2	9.00	2.52	0.22	08.73	EL506A-5	3/4	1/4	18 *	Incomplete cut; did not cut 3 inches of plate under cap.
354	18	1/2	9.00	2.52	0.21	08.33	EL506A-5	3/4	1/4	18 *	Incomplete cut; same as test shot 353.
355	18	1/2	9.00	2.52	0.23	09.12	C-4	3/4	1/4	18 *	Incomplete cut, same as test shot 353.
356	18	1/2	9.00	2.52	0.25	09.92	C-4	3/4	1/4	18 *	Complete cut.
357	18	1/2	9.00	2.52	0.25	09.92	C-4	3/4	1/4	18 *	Complete cut.
358	18	1/2	9.00	2.52	0.24	09.52	C-4	3/4	1/4	18 *	Complete cut
359	18	1/2	9.00	2.52	0.25	09.92	C-4	3/4	1/4	18 *	Complete cut.
360	18	1/2	9.00	2.52	0.29	11.51	C-4	3/4	1/4	18 *	Complete cut.
361	18	1/2	9.00	2.52	0.29	11.51	EL506A-5	1	1/4	18 *	Complete cut.
362	18	1/2	9.00	2.52	0.30	11.91	EL506A-5	1	1/4	18 *	Complete cut.
363	18	1/2	9.00	2.52	0.29	11.51	EL506A-5	1	1/4	18 *	Complete cut.
364	18	1/2	9.00	2.52	0.31	12.30	EL506A-5	1	1/4	18 *	Complete cut
365	18	1/2	9.00	2.52	0.30	11.91	EL506A-5	1	1/4	18 *	Complete cut.
366	18	1/2	9.00	2.52	0.24	09.52	EL506A-5	3/4	1/4	18 *	Complete cut.
367	18	1/2	9.00	2.52	0.22	08.73	EL506A-5	3/4	1/4	18 *	Complete cut.
368	18	1/4	4.50	1.26	0.07	05.56	EL506A-5	3/8	1/8	18 *	Incomplete cut for same reason as test shot 353.
369	18	1/4	4.50	1.26	0.07	05.56	EL506A-5	3/8	1/8	18 *	Complete cut.
370	18	1/4	4.50	1.26	0.07	05.56	EL506A-5	3/8	1/8	18 *	Complete cut.

Table XVI (cont'd)

Test Shot	Plate Dimension (in.)			Explosive Charge								Results
	Length	Thickness	Cross-Sectional Area (in.)²	Weight (lb) Calculated $P = \frac{3/8\,A}{1.34}$	Weight (lb) Actual	Percentage of P = 3/8A to Actual	Kind of Explosive	Dimension (in.) Width	Dimension (in.) Thickness	Dimension (in.) Length		
371	18	1/4	4.50	1.26	0.06	04.77	EL506A-5	3/8	1/8	18 *		Complete cut
372	18	1/4	4.50	1.26	0.08	06 35	EL506A-5	3/8	1/8	18 *		Complete cut.
373	18	1/4	4.50	1.26	0.15	11.91	EL506A-5	1/2	1/4	18 *		Complete cut.
374	18	1/4	4.50	1.26	0.16	12.70	EL506A-5	1/2	1/4	18 *		Complete cut.
375	18	1/4	4.50	1.26	0.15	11.91	EL506A-5	1/2	1/4	18 *		Complete cut.
376	18	1/4	4.50	1.26	0.14	11.12	EL506A-5	1/2	1/4	18 *		Complete cut.
377	18	1/4	4.50	1.26	0 14	11.12	EL506A-5	1/2	1/4	18 *		Complete cut.
378	18	1/4	4.50	1.26	0.18	14.29	C-4	1/2	1/4	18 *		Complete cut.
379	18	1/4	4.50	1.26	0.17	13.50	C-4	1/2	1/4	18 *		Incomplete cut, for same reason as in test shot 353.
380	18	1/4	4.50	1.26	0.17	13.50	C-4	1/2	1/4	18 *		Complete cut.
384	18	3	54.00	15.12	6.98	46.17	C-4	4-1/2	1-1/2	18 *		Complete cut
385	18	3	54.00	15.12	6.92	45.10	C-4	4-1/2	1-1/2	18 *		Borderline complete cut.
386	18	3	54.00	15.12	6.93	45.11	C-4	4-1/2	1-1/2	18 *		Complete cut.
387	18	3	54.00	15.12	6.67	44.12	C-4	4-1/2	1-1/2	18 *		Incomplete cut, 1/8-in. thickness of steel uncut
388	18	3	54 00	15.12	7.49	49.53	C-4	4-1/2	1-9/16	18 *		Complete cut
392	18	3	54.00	15.12	6.98	46.17	C-4	4-1/2	1-1/2	18 *		Complete cut
393	18	3	54.00	15.12	6.97	46.04	C-4	4-1/2	1-1/2	18 *		Complete cut.
394	18	3	54.00	15.12	6.98	46.17	C-4	4-1/2	1-1/2	18 *		Complete cut.

* Indicates charges that were primed and detonated at the center; all others were primed and detonated at one end.

Table XVII. Summary of Explosive-Cutting Test Results on Structural Steel Angles

Test Shot	Structural Steel Shape						Explosive Charge						
	Shape	Dimension (in.)				Cross-Sectional Area (in.)^2	Weight (lb)		Percentage of P = 3/8 A to Actual	Kind of Explosive	Dimension (in.)		
		Leg One		Leg Two			Calculated	Actual			Width	Thickness	Length
		Width	Thickness	Width	Thickness		$P = \frac{3/8\,A}{1.34}$						
11	5 x 3½ Angle	5	1/4	3-1/4	1/4	2.06	0.58	0.38	65.51	Paste	1-1/8	13/16	8-1/4
15	5 x 3½ Angle	5	1/4	3-1/4	1/4	2.06	0.58	0.21	36.20	Paste	1-1/4	5/8	8-1/4
16	5 x 3½ Angle	5	1/4	3-1/4	1/4	2.06	0.58	0.19	32.75	Paste	1-1/8	5/8	8-1/4
17	5 x 3½ Angle	5	1/4	3-1/4	1/4	2.06	0.58	0.18	31.03	Paste	1-1/8	9/16	8-1/4
120	4 x 3½ Angle	4	3/8	3-1/8	3/8	2.67	0.75	0.28	37.33	Paste	1-3/16	5/8	7
215	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.36	29.05	C-4	2-3/4	11/16	16 *
216	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.32	28.20	Paste	2-3/4	11/16	16 *
217	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.12	23.89	EL506A-5	2-3/4	9/16	16
218	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.31	27.99	C-4	2-3/4	11/16	16
219	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.21	25.85	Paste	2-3/4	1/2	16
220	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.10	23.50	Paste	2-5/8	1/2	16
221	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	0.99	21.15	Paste	2-1/2	1/2	16
222	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	0.99	21.15	Paste	2-1/2	1/2	16
223	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.48	31.60	C-4	2-3/4	11/16	16
223a	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.48	31.60	C-4	2-3/4	11/16	16
223b	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.12	23.89	EL506A-5	2-3/4	9/16	16
223c	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.12	23.89	EL506A-5	2-3/4	9/16	16
223d	8 x 8 Angle	8	1-1/8	8	1-1/8	16.73	4.68	1.12	23.89	EL506A-5	2-3/4	9/16	16

Note These explosive-cutting test shots all resulted in complete cuts
* Signifies charges primed and detonated at one end, all other charges were primed and detonated at the center

Table XVIII. Summary of Explosive-Cutting Test Results on Steel Beams and Channels

Test Shot	Shape	Structural Steel Shape: Dimension (in.) Flange Width	Flange Thickness	Web Depth	Web Thickness	Cross-Sectional Area (in.)^2	Explosive Charge: Weight (lb) Calculated $P = \frac{3/8\ A}{1.34}$	Actual	Percentage of P = 3/8A to Actual	Kind of Explosive	Dimension (in.) Flange Charge Width	Flange Charge Thickness	Web Char[ge] Width	Thic[kness]
12	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.37	33.29	Paste[(a)]	2-1/4	5/8	1-3/4	5[illegible]
18	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.89	21.65	Paste[(a)]	1-1/4	9/16	1-1/4	9[illegible]
19	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.97	23.60	Paste[(b)]	1-1/4	9/16	1-1/4	9[illegible]
28	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.37	33.99	Paste[(b)]	1-1/4	9/16	1-1/4	9[illegible]
31	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.79	19.22	Paste[(a)]	1-1/4	5/8	1-1/4	1[illegible]
32	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.82	19.95	Paste[(a)]	1-1/4	5/8	1-1/8	1[illegible]
33	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.82	19.95	Paste[(c)]	1-1/4	5/8	1-1/8	1[illegible]
34	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.87	21.16	Paste[(c)]	1-1/4	5/8	1-1/4	1[illegible]
35	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.88	21.41	Paste[(c)]	1-1/4	5/8	1-1/8	5[illegible]
36	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.31	32.50	Paste[(a)]	1-3/4	11/16	1-1/2	9[illegible]
37	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.12	2[illegible] 25	Paste[(a)]	1-3/4	11/16	1-1/2	9[illegible]
39	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.15	27 98	Paste[(a)]	2	3/4	1-1/4	5[illegible]
40	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.04	25.30	Paste[(a)]	2	3/4	1-1/4	5[illegible]
41	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.00	24.33	Paste[(d)]	1	1/2	1	[illegible]
42	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.92	22.38	Paste[(d)]	1	1/2	1	[illegible]
43	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.01	24.57	Paste[(d)]	1	1/2	1	[illegible]
44	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.96	23.35	Paste[(d)]	1	1/2	1	[illegible]

...le XVIII. Summary of Explosive-Cutting Test Results on Steel Beams and Channels

...el Shape (in.)		Cross-Sectional Area (in.)^2	Weight (lb)		Percentage of P = 3/8 A to Actual	Explosive Charge						Result
Web			Calculated	Actual		Kind of Explosive	Dimension (in.)					
							Flange Charge		Web Charge			
...epth	Thickness		$P = \frac{3/8\ A}{1.34}$				Width	Thickness	Width	Thickness		
5	3/8	14.70	4.11	1.37	33.29	Paste[a]	2-1/4	5/8	1-3/4	5/8		Complete cut.
5	3/8	14.70	4.11	0.89	21.65	Paste[a]	1-1/4	9/16	1-1/4	9/16		Complete cut.
5	3/8	14.70	4.11	0.97	23.60	Paste[b]	1-1/4	9/16	1-1/4	9/16		Complete cut.
8-7/8	3/8	14.40	4.03	1.37	33.99	Paste[b]	1-1/4	9/16	1-1/4	9/16		Complete cut
5	3/8	14.70	4.11	0.79	19.22	Paste[a]	1-1/4	5/8	1-1/4	1/2		Incomplete cut; did not cut top flange on side of web charge or fillet, as flange charge offset was too great
5	3/8	14.70	4.11	0.82	19.95	Paste[a]	1-1/4	5/8	1-1/8	1/2		Incomplete cut, cut all but top flange on side of web charge.
5	3/8	14.70	4.11	0.82	19.95	Paste[c]	1-1/4	5/8	1-1/8	1/2		Complete cut.
5	3/8	14.70	4.11	0.87	21.16	Paste[c]	1-1/4	5/8	1-1/4	1/2		Incomplete cut; did not cut web and half bottom flange because charge did not detonate on those areas.
5	3/8	14.70	4.11	0.88	21.41	Paste[c]	1-1/4	5/8	1-1/8	5/8		Incomplete cut; same results as test shot 34.
8-7/8	3/8	14.40	4.03	1.31	32.50	Paste[a]	1-3/4	11/16	1-1/2	9/16		Complete cut.
5	3/8	14.70	4.11	1.12	27.25	Paste[a]	1-3/4	11/16	1-1/2	9/16		Incomplete cut; did not cut top flange on side of web charge.
5	3/8	14.70	4.11	1.15	27.98	Paste[a]	2	3/4	1-1/4	5/8		Incomplete cut; same results as test shot 34.
5	3/8	14.70	4.11	1.04	25.30	Paste[a]	2	3/4	1-1/4	5/8		Incomplete cut; did not cut ½ of top flange on side opposite web charge.
	3/8	14.70	4.11	1.00	24.33	Paste[d]	1	1/2	1	1/2		Incomplete cut; did not cut fillet of beam because charge offset was too great.
	3/8	14.70	4.11	0.92	22.38	Paste[d]	1	1/2	1	1/2		Incomplete cut; did not cut ½ of bottom flange.
	3/8	14.70	4.11	1.01	24.57	Paste[d]	1	1/2	1	1/2		Complete cut.
	3/8	14.70	4.11	0.96	23.35	Paste[d]	1	1/2	1	1/2		Complete cut.

2

Table XVIII (cont'd)

Test Shot	Shape	Structural Steel Shape: Dimension (in.): Flange Width	Flange Thickness	Web Depth	Web Thickness	Cross-Sectional Area (in.)^2	Explosive Charge: Weight (lb): Calculated $P = \frac{3/8\ A}{1.34}$	Actual	Percentage of P=3/8A to Actual	Kind of Explosive	Dimensi[on]: Flange Charge Width	Thickness
45	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.85	20.68	Paste[d]	1	1/2
46	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.09	26.52	Paste[d]	1	1/2
47	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.92	22.38	Paste[d]	1	1/2
48	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.10	26.76	Paste[d]	1	1/2
49	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.09	26.52	Paste[d]	1	1/2
50	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.04	25.30	Paste[d]	1	1/2
51	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.06	25.43	Paste[d]	1	1/2
52	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.19	28.95	C-4[d]	1	1/2
53	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.04	25.30	Paste[d]	1	1/2
54	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.14	[illegible]	Paste[d]	1	1/2
55	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.26	30.65	C-4[d]	1	1/2
56	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.16	28.22	Paste[d]	1	1/2
57	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.26	30.65	Paste[d]	1	1/2
58	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.32	32.87	Paste[d]	1	1/2
59	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.01	25.06	C-4[d]	1	1/2
60	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.29	32.01	Paste[e]	1	1/2
61	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.20	29.77	Paste[e]	1	1/2
62	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.18	28.71	Paste[e]	1	1/2
63	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.05	26.07	Paste[e]	1	1/2
64	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.16	28.22	Paste[e]	1	1/2
65	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.12	27.25	Paste[e]	1	1/2

Table XVIII (cont'd)

tural Steel Shape							Explosive Charge						
ension (in.)			Cross-Sectional Area (in.)^2	Weight (lb)		Percentage of P = 3/8 A to Actual	Kind of Explosive	Dimension (in.)				Result
	Web			Calculated	Actual			Flange Charge		Web Charge		
ess	Depth	Thickness		$P = \frac{3/8\ A}{1.34}$				Width	Thickness	Width	Thickness	
	15	3/8	14.70	4.11	0.85	20.68	Paste(d)	1	1/2	1	1/2	Incomplete cut; did not cut ½ of top flange.
	15	3/8	14.70	4.11	1.09	26.52	Paste(d)	1	1/2	1	1/2	Complete cut
	15	3/8	14.70	4.11	0.92	22.38	Paste(d)	1	1/2	1	1/2	Incomplete cut; flanges on one side were not cut.
	15	3/8	14.70	4.11	1.10	26.76	Paste(d)	1	1/2	1	1/2	Complete cut
	15	3/8	14.70	4.11	1.09	26.52	Paste(d)	1	1/2	1	1/2	Complete cut.
	15	3/8	14.70	4.11	1.04	25.30	Paste(d)	1	1/2	1	1/2	Complete cut.
	8-7/8	3/8	14.40	4.03	1.06	25.43	Paste(d)	1	1/2	1	1/2	Incomplete cut, did not cut flanges on one side of beam.
	15	3/8	14.70	4.11	1.19	28.95	C-4(d)	1	1/2	1	1/2	Complete cut.
	15	3/8	14.70	4.11	1.04	25.30	Paste(d)	1	1/2	1	1/2	Incomplete cut; did not cut ½ of bottom flange.
	15	3/8	14.70	4.11	1.14	27.73	Paste(d)	1	1/2	1	1/2	Incomplete cut, did not cut flanges on one side of beam, as charge on that side did not detonate.
	15	3/8	14.70	4.11	1.26	30.65	C-4(d)	1	1/2	1	1/2	Complete cut.
	15	3/8	14.70	4.11	1.16	28.22	Paste(d)	1	1/2	1	1/2	Complete cut.
	15	3/8	14.70	4.11	1.26	30.65	Paste(d)	1	1/2	1	1/2	Complete cut
	8-7/8	3/8	14.40	4.03	1.32	32.87	Paste(d)	1	1/2	1	1/2	Complete cut.
	8-7/8	3/8	14.40	4.03	1.01	25.06	C-4(d)	1	1/2	1	1/2	Complete cut
	8-7/8	3/8	14.40	4.03	1.29	32.01	Paste(e)	1	1/2	1	1/2	Complete cut.
	8-7/8	3/8	14.40	4.03	1.20	29.77	Paste(e)	1	1/2	1	1/2	Complete cut.
	15	3/8	14.70	4.11	1.18	28.71	Paste(e)	1	1/2	1	1/2	Complete cut.
	8-7/8	3/8	14.40	4.03	1.05	26.07	Paste(e)	1	1/2	1	1/2	Incomplete cut; did not cut flange on one side of beam because charge on that side did not detonate.
	15	3/8	14.70	4.11	1.16	28.22	Paste(e)	1	1/2	1	1/2	Complete cut.
	15	3/8	14.70	4.11	1.12	27.25	Paste(e)	1	1/2	1	1/2	Incomplete cut; same results as test shot 63.

2

Table XVIII (cont'd)

Test Shot	Shape	Structural Steel Shape: Dimension (in.) Flange Width	Flange Thickness	Web Depth	Web Thickness	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\ A}{1.34}$	Weight (lb) Actual	Percentage of P=3/8A to Actual	Explosive Charge: Kind of Explosive	Dimension (in.) Flange Charge Width	Flange Charge Thickness	W[e]… Widt[h]…
66	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.21	29.44	Paste[e]	1	1/2	1
67	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.32	32.11	Paste[e]	1	1/2	1
68	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.03	25.06	Paste[e]	1	1/2	1
69	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.87	21.16	Paste[e]	1	1/2	1
70	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.00	24.33	C-4[d]	3/4	1/2	3/
71	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.99	24.08	C-4[d]	3/4	1/2	3/
72	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.99	24.08	C-4[e]	3/4	1/2	3/
73	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.10	26.76	C-4[e]	3/4	1/2	3/
74	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.10	26.76	C-4[e]	3/4	1/2	3/
75	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.99	24.08	C-4[e]	3/4	1/2	3/
76	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.18	28.71	Paste[e]	3/4	1/2	3/
77	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.05	25.54	C-4[e]	3/4	1/2	3/
78	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.02	24.81	Paste[e]	3/4	1/2	3/
87	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.07	26.55	Paste[e]	1	1/2	1
88	10WF49 Beam	10	9/16	8-7/8	3/8	14.40	4.03	1.01	26.06	C-4[e]	1	1/2	1
192	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.93	31.69	C-4[b]	2-1/8	17/32	1-3
193	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.90	31.19	EL506A-5[b]	2-1/8	9/16	1-3
194	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.98	32.51	Paste[b]	2-1/8	9/16	1-1
195	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.98	32.51	Paste[b]	2-1/8	9/16	1-1
196	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	2.00	32.84	C-4[b]	2-1/8	17/32	1-3
197	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.46	23.97	EL506A-5[b]	2-1/8	3/8	1-3
198	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.90	31.19	Paste[b]	2-1/8	17/32	1-3
199	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.87	30.70	Paste[b]	2-1/8	17/32	1-3
200	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.98	32.51	C-4[b]	2-1/8	17/32	1-3

Table XVIII (cont'd)

hape		Explosive Charge									
Veb		Cross-Sectional Area $(in.)^2$	Weight (lb)		Percentage of P = 3/8A to Actual	Kind of Explosive	Dimension (in.)				Result
			Calculated $P = \frac{3/8\,A}{1.34}$	Actual			Flange Charge		Web Charge		
	Thickness						Width	Thickness	Width	Thickness	
	3/8	14.70	4.11	1.21	29.44	Paste[e]	1	1/2	1	1/2	Complete cut
	3/8	14.70	4.11	1.32	32.11	Paste[e]	1	1/2	1	1/2	Complete cut.
	3/8	14.70	4.11	1.03	25.06	Paste[e]	1	1/2	1	1/2	Complete cut.
	3/8	14.70	4.11	0.87	21.16	Paste[e]	1	1/2	1	1/2	Complete cut.
	3/8	14.70	4.11	1.00	24.33	C-4[d]	3/4	1/2	3/4	1/2	Incomplete cut, did not cut flanges on one side.
	3/8	14.70	4.11	0.99	24.08	C-4[d]	3/4	1/2	3/4	1/2	Incomplete cut; same results as test shot 70.
	3/8	14.70	4.11	0.99	24.08	C-4[e]	3/4	1/2	3/4	1/2	Complete cut
	3/8	14.70	4.11	1.10	26.76	C-4[e]	3/4	1/2	3/4	1/2	Complete cut.
	3/8	14.70	4.11	1.10	26.76	C-4[e]	3/4	1/2	3/4	1/2	Complete cut.
	3/8	14.70	4.11	0.99	24.08	C-4[e]	3/4	1/2	3/4	1/2	Complete cut
	3/8	14.70	4.11	1.18	28.71	Paste[e]	3/4	1/2	3/4	1/2	Complete cut.
	3/8	14.70	4.11	1.05	25.54	C-4[e]	3/4	1/2	3/4	1/2	Complete cut.
	3/8	14.70	4.11	1.02	24.81	Paste[e]	3/4	1/2	3/4	1/2	Complete cut.
/8	3/8	14.40	4.03	1.07	26.55	Paste[e]	1	1/2	1	1/2	Complete cut.
/8	3/8	14.40	4.03	1.01	26.06	C-4[e]	1	1/2	1	1/2	Complete cut.
/8	7/16	21.76	6.09	1.93	31.69	C-4[b]	2-1/8	17/32	1-3/8	11/32	Complete cut.
/8	7/16	21.76	6.09	1.90	31.19	EL506A-5[b]	2-1/8	9/16	1-3/8	3/8	Complete cut.
/8	7/16	21.76	6.09	1.98	32.51	Paste[b]	2-1/8	9/16	1-1/2	1/2	Complete cut.
/8	7/16	21.76	6.09	1.98	32.51	Paste[b]	2-1/8	9/16	1-1/2	1/2	Complete cut.
/8	7/16	21.76	6.09	2.00	32.84	C-4[b]	2-1/8	17/32	1-3/8	11/32	Complete cut.
/8	7/16	21.76	6.09	1.46	23.97	EL506A-5[b]	2-1/8	3/8	1-3/8	3/8	Complete cut.
/8	7/16	21.76	6.09	1.90	31.19	Paste[b]	2-1/8	17/32	1-3/8	11/32	Complete cut.
/8	7/16	21.76	6.09	1.87	30.70	Paste[b]	2-1/8	17/32	1-3/8	11/32	Complete cut
/8	7/16	21.76	6.09	1.98	32.51	C-4[b]	2-1/8	17/32	1-3/8	11/32	Complete cut.

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Table XVIII (cont'd)

Test Shot	Structural Steel Shape: Shape	Dimension (in.) Flange Width	Flange Thickness	Web Depth	Web Thickness	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\,A}{1.34}$	Actual	Percentage of P = 3/8 A to Actual	Explosive Charge: Kind of Explosive	Dimension (in.) Flange Charge Width	Flange Charge Thickness	Wi
201	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.43	23.48	EL506A-5(b)	2-1/8	3/8	1-
202	14WF74 Beam	10-1/8	13/16	12-5/8	7/16	21.76	6.09	1.98	32.51	Paste(b)	2-1/8	17/32	1-
224	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.52	24.28	C-4(b)	1-7/8	15/32	1-
225	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.42	22.63	C-4(b)	1-7/8	15/32	1-
226	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.74	27.79	Paste(b)	1-7/8	15/32	1-
227	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.65	26.35	Paste(b)	1-7/8	15/32	1-
228	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.76	28.11	Paste(b)	1-7/8	15/32	1-
229	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.70	27.15	EL506A-5(b)	1-7/8	9/16	1-
230	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.76	28.11	Paste(b)	1-7/8	15/32	1-
231	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.26	20.12	C-4(b)	1-1/2	1/2	1-
232	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.64	26.19	Paste(b)	1-1/2	1/2	1-
233	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.34	21.41	C-4(b)	1-1/2	1/2	1-
234	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	0.90	14.37	EL506A-5(b)	1-1/2	3/8	1-
237	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.72	28.11	Paste(b)	1-1/2	1/2	1-
238	24WF76 Beam	9	11/16	22-1/2	7/16	22.37	6.26	1.29	20.60	EL506A-5(b)	1-1/2	9/16	1-
239	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.84	20.40	C-4	1-3/8	15/32	1
240	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.88	21.36	Paste	1-3/8	15/32	1
241	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.88	21.36	EL506A-5	1-3/8	3/8	1
242	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1
243	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1
244	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1
245	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.87	21.11	C-4	1-3/8	15/32	1
246	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1
247	15 x 3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.86	20.87	Paste	1-3/8	3/8	1

Table XVIII (cont'd)

l Shape n.) /eb Thickness	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\,A}{1.34}$	Weight (lb) Actual	Percentage of P = 3/8 A to Actual	Explosive Charge Kind of Explosive	Dimension (in.) Flange Charge Width	Flange Charge Thickness	Web Charge Width	Web Charge Thickness	Result
7/16	21.76	6.09	1.43	23.48	EL506A-5[b]	2-1/8	3/8	1-3/8	3/8	Incomplete cut; did not cut flanges because flange charges were too thin.
7/16	21.76	6.09	1.98	32.51	Paste[b]	2-1/8	17/32	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.52	24.28	C-4[b]	1-7/8	15/32	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.42	22.68	C-4[b]	1-7/8	15/32	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.74	27.79	Paste[b]	1-7/8	15/32	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.65	26.35	Paste[b]	1-7/8	15/32	1-3/8	11/32	Complete cut
7/16	22.37	6.26	1.76	28.11	Paste[b]	1-7/8	15/32	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.70	27.15	EL506A-5[b]	1-7/8	9/16	1-3/8	3/8	Complete cut.
7/16	22.37	6.26	1.76	28.11	Paste[b]	1-7/8	15/32	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.26	20.12	C-4[b]	1-1/2	1/2	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.64	26.19	Paste[b]	1-1/2	1/2	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	1.34	21.41	C-4[b]	1-1/2	1/2	1-3/8	11/32	Complete cut.
7/16	22.37	6.26	0.90	14.37	EL506A-3[b]	1-1/2	3/8	1-3/8	3/8	Incomplete cut, charges on flanges too thin and did not cut flanges.
7/16	22.37	6.26	1.72	28.11	Paste[b]	1-1/2	1/2	1-3/8	11/32	Complete cut
7/16	22.37	6.26	1.29	20.60	EL506A-5[b]	1-1/2	9/16	1-1/32	3/8	Complete cut.
3/4	14.64	4.12	0.84	20.40	C-4	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.88	21.36	Paste	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.88	21.36	EL506A-5	1-3/8	3/8	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.87	21.11	C-4	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1-11/16	9/16	Complete cut.
3/4	14.64	4.12	0.86	20.87	Paste	1-3/8	3/8	1-11/16	9/16	Complete cut.

2

Table XVIII (cont'd)

Test Shot	Shape	Structural Steel Shape: Dimension (in.): Flange Width	Flange Thickness	Web Depth	Web Thickness	Cross-Sectional Area (in.)^2	Explosive Charge: Weight (lb): Calculated $P = \frac{3/8\ A}{1.34}$	Actual	Percentage of P = 3/8 A to Actual	Kind of Explosive	Dimension (in: Flange Charge Width	Flange Charge Thickness	V…
248	15x3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.80	19.41	C-4	1-3/8	15/32	1
249	15x3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1
250	15x3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.81	19.66	C-4	1-3/8	15/32	1
251	15x3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.78	18.93	EL506A-5	1-3/8	3/8	1
251a	15x3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.78	18.93	EL506A-5	1-3/8	3/8	1
251b	15x3-3/8 Channel	3-3/4	5/8	13-3/4	3/4	14.64	4.12	0.78	18.93	EL506A-5	1-3/8	3/8	1
254	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.10	26.76	Paste(b)	1-1/8	3/8	
274	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.76	18.49	C-4(b)	1-1/8	3/8	
275	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.56	13.62	C-4(b)	1-1/8	3/8	
276	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.61	14.84	C-4(b)	1-1/8	3/8	
277	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.88	21.41	Paste(b)	1-1/8	3/8	
278	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.88	21.41	Paste(b)	1-1/8	3/8	
279	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	0.41	9.97	EL506A-5(b)	1-1/8	3/8	
280	16WF50 Beam	7-1/8	5/8	15	3/8	14.70	4.11	1.15	27.98	Paste(b)	1-1/8	1/2	1
298	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	7.73	31.33	C-4(b)	3	1	2
299	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	4.25	17.22	C-4(b)	2	3/4	1-
300	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	4.46	18.07	Paste(b)	2	3/4	1-
301	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	5.78	23.30	Paste(b)	2-1/2	11/16	1-
302	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	4.27	17.30	C-4(b)	3	1	2
303	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	6.60	26.75	Paste(b)	2-3/4	1	2
304	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	7.00	28.37	Paste(b)	3-1/4	3/4	2
304a	36WF300 Beam	16-5/8	1-11/16	33-3/8	1-5/16	88.17	24.67	7.00	28.37	Paste(b)	3-1/4	3/4	2
304b	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	4.25	17.22	C-4(b)	2	3/4	1-

Table XVIII (cont'd)

hape (in.) Web h	Thickness	Cross-Sectional Area (in.)^2	Explosive Charge Weight (lb) Calculated $P = \frac{3/8\ A}{1.34}$	Actual	Percentage of P = 3/8 A to Actual	Kind of Explosive	Dimension (in.) Flange Charge Width	Flange Charge Thickness	Web Charge Width	Web Charge Thickness	Result
/4	3/4	14.64	4.12	0.80	19.41	C-4	1-3/8	15/32	1-11/16	9/16	Complete cut.
/4	3/4	14.64	4.12	0.77	18.68	Paste	1-3/8	15/32	1-11/16	9/16	Complete cut.
/4	3/4	14.64	4.12	0.81	19.66	C-4	1-3/8	15/32	1-11/16	9/16	Complete cut.
/4	3/4	14.64	4.12	0.78	18.93	EL506A-5	1-3/8	3/8	1-11/16	9/16	Complete cut.
/4	3/4	14.64	4.12	0.78	18.93	EL506A-5	1-3/8	3/8	1-11/16	9/16	Complete cut.
/4	3/4	14.64	4.12	0.78	18.93	EL506A-5	1-3/8	3/8	1-11/16	9/16	Complete cut.
	3/8	14.70	4.11	1.10	26.76	Paste[b]	1-1/8	3/8	27/32	9/32	Complete cut.
	3/8	14.70	4.11	0.76	18.49	C-4[b]	1-1/8	3/8	27/32	9/32	Complete cut
	3/8	14.70	4.11	0.56	13.62	C-4[b]	1-1/8	3/8	27/32	9/32	Complete cut.
	3/8	14.70	4.11	0.61	14.84	C-4[b]	1-1/8	3/8	27/32	9/32	Complete cut.
	3/8	14.70	4.11	0.88	21.41	Paste[b]	1-1/8	3/8	27/32	9/32	Complete cut.
	3/8	14.70	4.11	0.88	21.41	Paste[b]	1-1/8	3/8	27/32	9/32	Complete cut.
	3/8	14.70	4.11	0.41	9.97	EL506A-5[b]	1-1/8	3/8	27/32	3/16	Incomplete cut; did not cut flanges, as flange charges were too thin.
	3/8	14.70	4.11	1.15	27.98	Paste[b]	1-1/8	1/2	1	1/2	Complete cut.
/8	15/16	88.17	24.67	7.73	31.33	C-4[b]	3	11	2	11/16	Complete cut.
/8	15/16	88.17	24.67	4.25	17.22	C-4[b]	2	3/4	1-1/2	1/2	Complete cut.
/8	15/16	88.17	24.67	4.46	18.07	Paste[b]	2	3/4	1-1/2	1/2	Incomplete cut, but beam was almost cut effectively; charge too thin.
/8	15/16	88.17	24.67	5.78	23.30	Paste[b]	2-1/2	11/16	1-3/4	11/16	Incomplete cut; same results as test shot 300.
/8	15/16	88.17	24.67	4.27	17.30	C-4[b]	3	1	2	11/16	Low-density C-4 explosive caused incomplete cut.
/8	15/16	88.17	24.67	6.60	26.75	Paste[b]	2-3/4	1	2	7/8	Complete cut.
/8	15/16	88.17	24.67	7.00	28.37	Paste[b]	3-1/4	3/4	2	5/8	Complete cut.
/8	1-5/16	88.17	24.67	7.00	28.37	Paste[b]	3-1/4	3/4	2	5/8	Complete cut.
/8	15/16	88.17	24.67	4.25	17.22	C-4[b]	2	3/4	1-1/2	1/2	Complete cut.

2

Table XVIII (cont'd)

Test Shot	Shape	Structural Steel Shape Dimension (in.) Flange Width	Flange Thickness	Web Depth	Web Thickness	Cross-Sectional Area (in.)^2	Explosive Charge Weight (lb) Calculated $P = \frac{3/8\ A}{1.34}$	Weight (lb) Actual	Percentage of P=3/8A to Actual	Kind of Explosive	Dimension (lb) Flange Charge Width	Flange Charge Thickness	Web Width
304c	36WF300 Beam	16-5/8	1-11/16	33-3/8	15/16	88.17	24.67	7.73	31.33	C-4(b)	3	1	2
305	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	13.27	37 86	C-4(b)	4-1/2	1-1/2	3
306	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	10.43	29.75	C-4(b)	4	1-1/4	3
307	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	13.27	37 74	Paste(b)	4-1/2	1-3/4	3-1/8
308	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	11.75	33.52	C-4(b)	4	1-1/2	3
309	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	12.19	34.77	C-4(b)	4	1-1/2	3
309a	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	13.27	37.74	Paste(b)	4-1/2	1-3/4	3-1/8
309b	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	13.27	37.74	Paste(b)	4-1/2	1-3/4	3-1/8
309c	14WF426 Beam	16-3/4	3-1/16	12-5/8	1-7/8	125.25	35.05	13.27	37.74	Paste(b)	4-1/2	1-3/4	3-1/8
312	16WF50	7-1/8	5/8	15	3/8	14.70	4.11	1.10	26.76	Paste(a)	1-3/4	5/8	1-1/2
313	16WF50	7-1/8	5/8	15	3/8	14.70	4.11	1.32	32.11	Paste(a)	1-3/4	3/4	1-1/2
313a	16WF50	7-1/8	5/8	15	3/8	14.70	4.11	1.09	26.52	Paste(b)	1-3/4	5/8	1-1/2

Notes

(a) One continuous charge on the two half flanges and web -- one side of the beam, with the charge center primed with either a J-2 or T-6 (test m charges, one on each half of the top and bottom flanges on the opposite side of the beam, were offset 1 inch from the flange portion of the cont a J-2 or T-6 electric cap.

(b) Same basic charge placement but with less offset between half flange charges and continuous charge and same charge priming points as descri detonating cord, each having either a J-1 nonelectric cap or an overhand knot at the end, primed the one continuous and two flange charges for opposite ends of the three lengths of detonating, a J-2 electric cap exploded the detonating cord priming assembly.

(c) Same charge placement as described in footnote (a), but the continuous charge and the flange charges were end primed with either J-2 or T-6

(d) Continuous charges on the half flanges and web were offset slightly from each other on opposite sides of the beam, and a T-6 electric cap cent

(e) Same charge placement as described in footnote (d), but two lengths of detonating cord with either a J-1 cap or overhand knot at one end prim simultaneous detonation; a J-2 or T-6 electric cap initiated the detonating cord priming assembly.

Table XVIII (cont'd)

	Explosive Charge									
	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\,A}{1\ 34}$	Weight (lb) Actual	Percentage of P=3/8A to Actual	Kind of Explosive	Dimension (lb) Flange Charge Width	Flange Charge Thickness	Web Charge Width	Web Charge Thickness	Result
kness										
5/16	86.17	24.67	7.73	31.33	C-4[b]	3	1	2	11/16	Complete cut.
/8	125.25	35.05	13.27	37 86	C-4[b]	4-1/2	1-1/2	3	1	Complete cut
/8	125.25	35.05	10.43	29.75	C-4[b]	4	1-1/4	3	1-1/8	Incomplete cut, charges too thin.
/8	125.25	35.05	13.27	37 74	Paste[b]	4-1/2	1-3/4	3-1/8	1-1/4	Complete cut.
/8	125.25	35.05	11.75	33.52	C-4[b]	4	1-1/2	3	1	Complete cut
/8	125.25	35.05	12.19	34.77	C-4[b]	4	1-1/2	3	1	Complete cut.
/8	125.25	35.05	13.27	37.74	Paste[b]	4-1/2	1-3/4	3-1/8	1-1/4	Complete cut.
/8	125.25	35 05	13.27	37.74	Paste[b]	4-1/2	1-3/4	3-1/8	1-1/4	Complete cut.
/8	125.25	35.05	13.27	37.74	Paste[b]	4-1/2	1-3/4	3-1/8	1-1/4	Complete cut
3/8	14.70	4.11	1.10	26 76	Paste(a)	1-3/4	5/8	1-1/2	1/2	Incomplete cut, did not cut 2 flanges because of lack of simultaneous detonation of charges.
3/8	14.70	4.11	1.32	32.11	Paste[a]	1-3/4	3/4	1-1/2	1/2	Incomplete cut; same results as test shot 312.
3/8	14.70	4.11	1.09	26.52	Paste[b]	1-3/4	5/8	1-1/2	1/2	Complete cut.

nges and web -- one side of the beam, with the charge center primed with either a J-2 or T-6 (test model of M6 cap) electric blasting cap. two ottom flanges on the opposite side of the beam, were offset 1 inch from the flange portion of the continuous charge and end primed with either

s offset between half flange charges and continuous charge and same charge priming points as described in footnote (a), but three lengths of nonelectric cap or an overhand knot at the end, primed the one continuous and two flange charges for simultaneous detonation; fastened to the nating, a J-2 electric cap exploded the detonating cord priming assembly.

ootnote (a), but the continuous charge and the flange charges were end primed with either J-2 or T-6 electric caps.

d web were offset slightly from each other on opposite sides of the beam, and a T-6 electric cap center primed each of the charges

ootnote (d), but two lengths of detonating cord with either a J-1 cap or overhand knot at one end primed the two continuous charges for ectric cap initiated the detonating cord priming assembly.

2

Table XIX. Summary of Explosive-Cutting Test Results on Wire Ropes

Test Shot	Improved Plow-Steel Wire Rope: Diameter (in.)	No. of Strands	Wire per Strand	Explosive Charge: Weight (lb) Calculated $P = \frac{D^2}{1.34}$	Actual	Percentage of $P = \frac{D^2}{1.34}$ to Actual	Kind of Explosive	Placement	Priming	Result
116	1	6	19	0.75	0.49	65.33	Paste	Single charge on one side.	Center primed with M-6 cap.	Incomplete cut; 1 strand uncut
117	1	6	19	0.75	0.49	65.33	Paste	Single charge on one side.	Center primed with M-6 cap.	Incomplete cut; 5 wires uncut.
118	1	6	19	0.75	0.54	72.00	Paste	Single charge on one side.	Same as test shot 116.	Incomplete cut; 1 wire uncut.
119	1	6	19	0.75	0.54	72.00	Paste	Single charge on one side.	Same as test shot 116.	Complete cut.
126	1	6	19	0.75	0.54	72.00	Paste	Single charge on one side.	Center primed with M-6 cap.	Incomplete cut, 2 wires uncut.
127	1	6	19	0.75	0.54	72.00	Paste	Single charge on one side.	Center primed with M-6 cap.	Incomplete cut, 5 wires uncut.
128	1	6	19	0.75	0.55	73.33	Paste	One-half explosive on opposite sides with 1-inch overlap.	J-1 caps on D-cord bridle primed with J-2 cap.	Complete cut.
129	1	6	19	0.75	0.49	65.33	Paste	Same as test shot 128.	Same as test shot 128.	Complete cut.
130	1	6	19	0.75	0.44	58.66	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 9 wires uncut.
133	1-1/2	7	7	1.68	0.55	32.73	Paste	Same as test shot 128.	Same as test [illegible] ot 128.	Incomplete cut; 1 wire uncut.
134	1-1/2	7	7	1.68	0.57	33.92	Paste	Same as test shot 128.	Same as test shot 128.	Complete cut
135	1-1/2	7	7	1.68	0.5[illegible]	32.73	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 6 wires uncut.

Table XIX (cont'd)

Test Shot	Improved Plow-Steel Wire Rope: Diameter (in.)	No. of Strands	Wire per Strand	Explosive Charge: Weight (lb) Calculated $P = \frac{D^2}{1.34}$	Actual	Percentage of $P = \frac{D^2}{1.34}$ to Actual	Kind of Explosive	Placement	Priming	Result
136	1-1/2	7	7	1.68	0.57	33.92	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 2 wires uncut
137	1-1/2	7	7	1.68	0.60	35.71	Paste	Same as test shot 128.	Same as test shot 128.	Complete cut.
138	1-1/2	7	7	1.68	0.60	35.71	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 1 wire uncut.
139	1-1/2	7	7	1.68	0.60	35.71	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut; 3 wires uncut.
140	1-1/2	7	7	1.68	0.66	39.28	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 3 wires uncut
141	1-1/2	7	7	1.68	0.66	39.28	Paste	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 2 wires uncut.
142	1-1/2	7	7	1.68	0.66	39.28	Paste	Same as test shot 128.	Same as test shot 128.	Complete cut.
143	1-1/2	7	7	1.68	0.66	39.28	C-4	Same as test shot 128.	Same as test shot 128.	Complete cut.
144	1-1/2	7	7	1.68	0.66	39.28	C-4	Same as test shot 128.	Same as test shot 128.	Incomplete cut, 2 wires uncut.
145	1-1/2	7	7	1.68	0.66	39.28	C-4	Same as test shot 128.	Same as test shot 128.	Complete cut.
146	1-1/2	7	7	1.68	0.66	39.28	C-4	Same as test shot 128.	Same as test shot 128.	Complete cut.
147	1-1/2	7	7	1.68	0.57	33.92	C-4	Same as test shot 128.	Same as test shot 128.	Complete cut.
148	1-1/2	7	7	1.68	0.55	32.73	C-4	Same as test shot 128.	Same as test shot 128.	Incomplete cut; 1 wire uncut.

Table XX. Summary of Explosive-Cutting Test Results on Square Steel Bars (Cross-Fracture Charge Technique)

Test Shot	Square Bar Dimension (in.)			Explosive Charge							Result
	Width	Thickness	Cross-Sectional Area (in.)^2	Weight (lb) Calculated $P = \frac{3/8\ A}{1.34}$	Weight (lb) Actual	Percentage of P=3/8A to Actual	Kind of Explosive	Dimension (in.) Width	Dimension (in.) Thickness	Dimension (in.) Length	
79	2	2	4	1.12	0.69	61.60	Paste	2-1/4	7/8	7	Incomplete cut
80	2	2	4	1.12	0.62	55.35	Paste	2	1	6	Incomplete cut.
81	2	2	4	1.12	0.55	49.11	Paste	2	1	5	Complete cut.
82	2	2	4	1.12	0.58	51.78	C-4	2	1	5	Complete cut.
89	2	2	4	1.12	0.98	87.50	Paste	2-3/4	1-1/4	6	Complete cut.
90	2	2	4	1.12	0.97	86.60	Paste	2-1/4	1-1/4	7	Complete cut.
91	2	2	4	1.12	0.75	66.96	Paste	2	1-1/8	6-1/2	Incomplete cut.
92	2	2	4	1.12	0.77	68.75	Paste	2	1/4	6	Incomplete cut
93	2	2	4	1.12	0.83	74.10	Paste	2	1/4	6	Incomplete cut.
94	2	2	4	1.12	0.88	78.57	Paste	2	1/2	6	Complete cut.
95	2	2	4	1.12	0.86	76.78	Paste	2	1/2	6	Complete cut.
96	2	2	4	1.12	0.84	75.00	Paste	2	1/2	6	Incomplete cut.
97	2	2	4	1.12	0.86	76.78	Paste	2	1-1/4	8	Complete cut
98	2	2	4	1.12	0.86	76.78	Paste	2	2-1/2	4	Complete cut.
99	2	2	4	1.12	0.84	75.00	Paste	2	2	4	Incomplete cut.
100	2	2	4	1.12	0.84	75.00	Paste	2	1-1/4	8	Incomplete cut.
101	2	2	4	1.12	0.84	75.00	Paste	2	1	10	Incomplete cut.
102	2	2	4	1.12	0.84	75.00	Paste	2	7/8	12	Complete cut.
103	2	2	4	1.12	0.84	75.00	Paste	2	3/4	12	Complete cut.
104	2	2	4	1.12	0.84	75.00	Paste	2	3/4	12	Complete cut.
105	2	2	4	1.12	0.84	75.00	Paste	2	3/4	12	Complete cut
106	2	2	4	1.12	0.84	75.00	Paste	2	3/4	12	Complete cut.
107	2	2	4	1.12	0.84	75.00	Paste	2	3/4	12	Complete cut.
108	2	2	4	1.12	0.84	75.00	Paste	2	3/4	12	Complete cut.
109	2	2	4	1.12	0.84	75.00	C-4	2	9/16	12	Incomplete cut
110	2	2	4	1.12	0.84	75.00	C-4	2	1-3/8	6	Complete cut
111	2	2	4	1.12	0.66	58.92	C-4	2	1-3/8	4	Incomplete cut.
112	2	2	4	1.12	0.66	58.92	C-4	2	3/4	2*	Incomplete cut.
113	2	2	4	1.12	0.84	75.00	C-4	2	1	2*	Complete cut.
167	4	4	16	4.48	2.24	50.00	Paste	4	7/8	10	Complete cut.
168	4	4	16	4.48	1.54	34.38	Paste	4	3/4	8	Incomplete cut
169	4	4	16	4.48	1.76	39.29	Paste	4	3/4	8-1/2	Incomplete cut.
170	4	4	16	4.48	1.98	44.19	Paste	4	3/4	9	Incomplete cut.
171	4	4	16	4.48	2.09	46.65	Paste	4	5/8	10	Complete cut.
172	4	4	16	4.48	1.76	39.29	C-4	4	1	7-1/2	Complete cut.
173	4	4	16	4.48	1.32	29.46	C-4	4	1	5-3/4	Complete cut.
174	4	4	16	4.48	1.10	24.55	C-4	4	1	5	Complete cut.
175	4	4	16	4.48	0.88	19.64	C-4	4	1	4	Incomplete cut.
176	4	4	16	4.48	0.99	22.09	C-4	4	1	4-1/2	Incomplete cut
177	4	4	16	4.48	1.10	24.55	C-4	4	1	2-3/8*	Incomplete cut.
178	4	4	16	4.48	2.21	49.33	C-4	4	1	4-7/8*	Complete cut.
179	4	4	16	4.48	1.54	34.38	C-4	4	1	3-1/8*	Incomplete cut.
180	4	4	16	4.48	1.76	39.29	C-4	4	1	3-3/4*	Complete cut

* Two charges of the indicated weight and configuration were offset on opposite sides of the bar.

Table XXI. Summary of Explosive-Cutting Test Results on Round Steel Bars (Cross-Fracture Charge Technique)

Test Shot	Round Bar Dimension (in.)			Explosive Charge							Result
	Diameter	Length	Cross-Sectional Area (in.)^2	Weight (lb) Calculated by Formula (a)	Weight (lb) Actual	Percentage of Formula to Actual	Kind of Explosive	Dimension (in.) Width	Dimension (in.) Thickness	Dimension (in.) Length	
5	2	18	3.14	2.99	0.36	12.04	Paste	2-1/2	1-1/4	5-1/2	Incomplete cut
6	2	18	3.14	2.99	0.65	31.74	Paste	6-3/4	5/16	6-1/2	Incomplete cut.
7	2	18	3.14	2.99	0.76	25.42	Paste	3-1/4	15/16	7	Incomplete cut.
8	2	18	3.14	2.99	1.12	37.46	Paste	3-1/2	7/8	7	Complete cut.
9	2	18	3.14	2.99	1.12	37.46	Paste	3-3/8	7/8	7	Incomplete cut.
10	2	18	3.14	2.99	1.03	34.45	Paste	3-5/16	15/16	6	Incomplete cut.
13	2	18	3.14	2.99	0.75	25.08	Paste	3-1/4	7/8	6	Incomplete cut.
14	2	18	3.14	2.99	0.60	20.07	Paste	4-3/4	13/16	6	Incomplete cut.
83	2	18	3.14	2.99	0.99	33.11	C-4	2-3/4	1	5	Incomplete cut.
84	2	18	3.14	2.99	1.26	42.14	C-4	3-3/4	1	5	Complete cut.
85	2	18	3.14	2.99	0.87	29.10	C-4	2-1/2	1	4	Incomplete cut.
86	2	18	3.14	2.99	0.99	33.11	C-4	3	1	5	Incomplete cut
132	2	18	3.14	2.99	0.99	33.11	C-4	2-3/4	1	5	Incomplete cut.
149	2	18	3.14	2.99	2.00	66.89	Paste	3	1	4(b)	Complete cut.
150	2	18	3.14	2.99	1.50	50.17	C-4	2-1/2	7/8	3-1/4(b)	Incomplete cut.
26	3	18	7.07	6.72	1.53	22.77	Paste	3-3/4	7/8	7	Incomplete cut.
27	3	18	7.07	6.72	2.21	32.89	Paste	4-1/4	15/16	8-1/4	Incomplete cut
38	3	18	7.07	6.72	2.97	44.20	Paste	5	1	9-1/2	Incomplete cut.
114	3	18	7.07	6.72	3.50	52.08	Paste	5-1/4	7/8	9	Incomplete cut.
115	3	18	7.07	6.72	3.54	52.68	C-4	4-3/4	1	10-3/4	Incomplete cut.
131	3	18	7.07	6.72	3.13	46.58	C-4	4-1/2	1	9	Incomplete cut.
151	3	18	7.07	6.72	3.99	59.37	C-4	3-1/2	1	7(b)	Complete cut.
152	3	18	7.07	6.72	3.75	55.83	C-4	4	1	13	Incomplete cut.
153	3	18	7.07	6.72	4.41	65.63	C-4	5	1-1/2	9	Incomplete cut.
154	3	18	7.07	6.72	3.97	59.08	Paste	4	2	8	Incomplete cut.
155	4	60	12.57	3.52	4.41	125.52	Paste	4	1-1/2	13	Complete cut; intensional overcharge.

Table XXI (co u d)

Test Shot	Round Bar Dimension (in.) Diameter	Length	Cross-Sectional Area (in.)^2	Explosive Charge: Weight (lb) Calculated by Formula (a)	Actual	Percentage of Formula to Actual	Kind of Explosive	Dimension (in.) Width	Thickness	Length	Result
156	4	18	12.57	3.52	4.41	125.5[illegible]	Paste	4	1-1/2	13	Complete cut.
157	4	60	12.57	3.52	3.08	87.50	Paste	4	1-3/4	11	Complete cut.
158	4	60	12.57	3.52	2.64	75.00	Paste	4	1-1/2	10	Complete cut.
159	4	60	12.57	3.52	1.76	50.00	Paste	3-1/2	3/4	8-1/4	Complete cut.
160	4	60	12.57	3.52	1.54	43.75	Paste	3-1/2	3/4	7-1/2	Incomplete cut.
161	4	60	12.57	3.52	1.65	46.87	Paste	3-1/2	3/4	7-1/2	Complete cut
162	4	60	12.57	3.52	1.10	31.25	C-4	4	1	4-3/4	Complete cut
163	4	60	12.57	3.52	0.88	25.00	C-4	4	1	4	Incomplete cut
164	4	60	12.57	3.52	0.99	28.12	C-4	4	1	4-1/4	Incomplete cut.
165	4	60	12.57	3.52	0.99	28.12	C-4	3	1-5/8	4-1/2	Incomplete cut.
166	4	60	12.57	3.52	0.99	28.12	Paste	4	1	4-1/2	Incomplete cut.
271	3	18	7.07	6.72	4.85	72.17	C-4	4	1	13	Complete cut.
272	3	18	7.07	6.72	1.88	27.98	C-4	4	1	7-1/2	Incomplete cut.
273	3	72	7.07	1.98	1.85	93.00	C-4	4	1	7-1/2	Complete cut.

Notes (a) Formula $P = \frac{D^2}{1.34}$ (pounds of TNT explosive equals the diameter squared divided by the effectiveness factor 1.34 for C-4 explosive) was used to calculate the charges for cutting the round bars 2 inches in diameter and the alloy-steel bars 3 inches in diameter, which were all 18 inches long. formula $P = \frac{3/8\,A}{1.34}$ (pounds of TNT explosive equals 3/8 of the cross-sectional area divided by 1.34 for converting to C-4 explosive) was used to calculate the other charges.

(b) Two charges of the indicated weight and configuration were offset on opposite sides of the bar.

Table XXII. Summary of Steel-Cutting Test Results Obtained with Saddle Charges (Cross-Fracture Charge Technique)

Test Shot	Round Bar Dimension (in.)			Triangular-Shaped Explosive Charge						Result
	Diameter	Length	Cross-Sectional Area $(in.)^2$	Weight (lb)		Percentage of Formula to Actual	Dimension (in.)			
				Calculated by Formula*	Actual		Base (1/2 Cir.)	Altitude (2 X Base)	Thickness (2/3" up to 6" Dia.) (1" up to 8" Dia.)	
214	2	60	3.14	2.98	0.41	13.76	1.571	3.141	2/3	Complete cut
264	4	60	12.57	3.52	1.72	48.86	6.25	12. [illegible]	2/3	Complete cut.
266	4	60	12.57	3.52	1.58	44.89	6.25	12.50	2/3	Complete cut
267	6	60	28.27	7.91	2.63	33.25	7.854	15.566	2/3	Incomplete cut because of insufficient explosive; charge was too short
288	6	60	28.27	7.91	3.78	47.79	9.425	18.850	2/3	Complete cut
290	6	60	28.27	7.91	3.66	46.27	9.425	18.850	2/3	Complete cut.
290a	2	60	3.14	2.98	0.41	13.76	1.571	3.141	2/3	Complete cut
290b	2	60	3.14	2.98	0.41	13.76	1.571	3.141	2/3	Complete cut.
290c	2	60	3.14	2.98	0.41	13.76	1.571	3.141	2/3	Complete cut.
290d	2	60	3.14	2.98	0.41	13.76	1.571	3.141	2/3	Complete cut
290e	4	60	12.57	3.52	1.72	48.86	6.25	12.50	2/3	Complete cut.
290f	4	60	12.57	3.52	1.72	48.86	6.25	12.50	2/3	Complete cut.
290g	4	60	12.57	3.52	1.72	48.86	6.25	12.50	2/3	Complete cut.
290h	6	60	28.27	7.91	3.66	46.27	9.425	18.850	2/3	Complete cut.
290i	6	60	28.27	7.91	3.66	46.27	9.425	18.850	2/3	Complete cut
290j	6	60	28.27	7.91	3.66	46.27	9.425	18.850	2/3	Complete cut.

Note: Composition C-4 was the only explosive used for these test shots.

* Formula $P = \frac{3/8\ A}{1.34}$ (pounds of TNT explosive equals 3/8 of the cross-sectional area divided by the effectiveness factor of 1.34 for converting pounds of TNT to pounds of C-4 explosive) was used to calculate the charges for the round bars greater than 2 inches in diameter.

formula $P = \frac{D^2}{1.34}$ (pounds of TNT explosive equals diameter squared divided by the effectiveness factor of 1.34) was used to calculate charges for cutting round bars 2 inches in diameter.

Table XXIII. Summary of Steel-Cutting Test Results Obtained with Diamond-Shaped Charges

Test Shot	Round Bar Dimension (in.) Diameter	Length	Cross-Sectional Area (in.)^2	Diamond-Shaped Explosive Charges: Weight (lb) Calculated by Formula (*)	Actual	Percentage of Formula to Actual	Kind of Explosive	Dimension (in.) Long Axis	Short Axis	Thickness	Result
203	3	60	7.07	1.98	0.84	42.42	C-4[(a)]	9	4-3/4	2/3	Complete cut.
203a	3	60	7.07	1.98	0.26	13.13	EL506A-5[(a)]	9	4-3/4	3/16**	Complete cut.
204	3	60	7.07	1.98	0.87	43.94	C-4[(a)]	9-1/2	4-7/8	2/3	Complete cut.
205	3	60	7.07	1.98	0.30	15.15	C-4[(a)]	9	4-7/8	1/4	Complete cut.
206	3	60	7.07	1.98	0.51	25.76	C-4[(a)]	9	4-1/2	2/3	Complete cut.
207	3	60	7.07	1.98	0.54	27.27	C-4[(b)]	9-3/4	4-7/8	2/3	Complete cut.
208	3	60	7.07	1.98	0.80	40.40	C-4[(b)]	5-1/2	4	1	Complete cut.
209	2	60	3.14	2.98	0.13	04.36	EL506A-5[(b)]	6-1/4	3-1/2	3/16**	Complete cut.
210	2	60	3.14	2.98	0.15	05.03	C-4[(a)]	5-1/4	3-1/4	1/4	Complete cut
211	2	60	3.14	2.98	0.30	10.06	C-4[(a)]	6-1/4	3-1/4	2/3	Complete cut
212	2	60	3.14	2.98	0.40	13.42	C-4[(b)]	6-1/4	3-1/4	2/3	Complete cut.
213	2	60	3.14	2.98	0.42	14.09	C-4[(b)]	6-1/2	3-3/16	2/3	Complete cut.
257	4	60	12.57	3.52	0.42	11.93	EL506A-5[(a)]	12	6	3/16**	Complete cut.
258	4	60	12.57	3.52	0.52	14.77	C-4[(a)]	12	6	1/4	Complete cut
260	4	60	12.57	3.52	1.10	31.25	C-4[(b)]	12	6	2/3	Complete cut.
262	4	60	12.57	3.52	1.43	40.63	C-4[(b)]	12	6	2/3	Complete cut
291	4	60	12.57	3.52	0.57	16.19	C-4[(a)]	12	6	1/4	Complete cut
292	4	60	12.57	3.52	0.52	14.77	C-4[(b)]	12	6	1/4	Complete cut
293	4	60	12.57	3.52	0.53	15.06	C-4[(b)]	12	6	1/4	Incomplete cut
294	4	60	12.57	3.52	0.49	13.92	C-4[(b)]	12	6	1/4	Complete cut.
295	4	60	12.57	3.52	0.54	15.34	C-4[(b)]	12	6	1/4	Complete cut.
296	4	60	12.57	3.52	0.41	11.65	EL506A-5[(b)]	12	6	3/16**	Incomplete cut
297	4	60	12.57	3.52	0.43	12.22	EL506A-5[(b)]	12	6	3/16**	Incomplete cut.
235	6	60	28.27	7.91	0.95	12.01	EL506A-5[(a)]	18	9	3/16**	Complete cut.
236	6	60	28.27	7.91	1.23	15.55	C-4[(a)]	18	9	1/4	Complete cut
252	6	60	28.27	7.91	0.90	11.37	EL506A-5[(a)]	18	9	3/16**	Complete cut
253	6	60	28.27	7.91	0.93	11.75	EL506A-5[(a)]	18	9	3/16**	Incomplete cut, charge too thin
255	6	18	28.27	7.91	3.53	44.62	C-4[(a)]	18	9	2/3	Incomplete cut, alloy steel.
256	6	60	28.27	7.91	1.49	18.83	C-4[(a)]	18	9	1/4	Complete cut.
263	6	60	28.27	7.91	2.36	29.83	C-4[(a)]	18	9	2/3	Complete cut
265	6	60	28.27	7.91	0.66	08.34	EL506A-5[(a)]	18	9	3/16**	Incomplete cut, charge too thin.
268	6	18	28.27	7.91	2.37	29.96	C-4[(a)]	18	9	2/3	Incomplete cut, alloy steel.
269	6	18	28.27	7.91	1.55	19.59	C-4[(b)]	18	9	1/4	Incomplete cut, alloy steel.
270	6	18	28.27	7.91	0.90	11.37	C-4[(b)]	18	9	1/4	Incomplete cut, alloy steel.

Table XXIII (cont'd)

Test Shot	Round Bar Dimension (in.) Diameter	Length	Cross-Sectional Area (in.)^2	Diamond-Shaped Explosive Charge: Weight (lb) Calculated by Formula (*)	Actual	Percentage of Formula to Actual	Kind of Explosive	Dimension (in.) Long Axis	Short Axis	Thickness	Result
281	6	60	28.27	7.91	1.18	14.91	C-4[a]	18	9	1/4	Complete cut.
282	6	60	28.27	7.91	1.06	13.40	C-4[a]	18	9	1/4	Complete cut.
283	6	60	28.27	7.91	0.88	11.12	EL506A-5[a]	18	9	3/16**	Incomplete cut; charge too thin.
284	6	60	28.27	7.91	0.90	11.37	EL506A-5[a]	18	9	3/16**	Incomplete cut; charge too thin.
285	6	60	28.27	7.91	1.09	13.78	C-4[a]	18	9	1/4	Incomplete cut.
286	6	60	28.27	7.91	1.36	17.19	C-4[a]	18	9	1/4	Complete cut.
287	6	60	28.27	7.91	1.15	14.53	C-4[b]	18	9	1/4	Incomplete cut.
289	6	60	28.27	7.91	1.10	13.90	C-4[b]	18	9	1/4	Incomplete cut.
337	6	60	28.27	7.91	0.88	11.12	EL506A-5[a]	18	9	3/16**	Incomplete cut.
338	6	60	28.27	7.91	1.18	14.91	C-4[a]	19	9	1/4	Complete cut.
349	4	60	16	4.48	0.48	10.72	EL506A-5[b]	13	6-1/2**	3/16	Incomplete cut; axes of charge too short.
381	4	60	16	4.48	0.67	14.96	EL506A-5	15	8**	3/16	Incomplete cut; axes of charge too short-1 inch uncut.
382	4	60	16	4.48	0.82	18.31	EL506A-5	17	8-1/2	3/16**	Complete cut.
383	4	60	16	4.48	0.82	18.31	EL506A-5	17	8-1/2	3/16**	Complete cut.
389	4	60	16	4.48	0.75	16.74	EL506A-5	16-1/2	8-1/4	3/16**	Complete cut.
390	4	60	16	4.48	2.20	49.11	C-4	16-1/2	8-1/4	1/2	Complete cut.
391	4	60	16	4.48	2.23	49.78	C-4	16-1/2	8-1/4	1/2	Complete cut.
395	4	60	16	4.48	2.22	49.56	C-4	16-1/2	8-1/4	1/2	Complete cut
396	4	60	16	4.48	2.20	49.11	C-4	16-1/2	8-1/4	1/2	Complete cut.
397	4	60	16	4.48	0.75	16.74	EL506A-5	16-1/2	8-1/4	3/16**	Complete cut.
398	4	60	16	4.48	0.75	16.74	EL506A-5	16-1/2	8-1/4	3/16**	Complete cut.
399	4	60	16	4.48	0.75	16.74	EL506A-5	16-1/2	8-1/4	3/16**	Complete cut.

Notes (a) and (b) signify charge initiation by detonating cord priming assembly and J-2 electric caps, respectively.

* Formula $P = \frac{D^2}{1.34}$ (pounds of TNT explosive equals the diameter squared divided by the effectiveness factor 1.34 for C-4 explosive) was used to calculate the charges for cutting round bars 2 inches in diameter; formula $P = \frac{3/8\ A}{1.34}$ (pounds of TNT explosive equals 3/8 of the cross-sectional area divided by the effectiveness factor of 1.34 for converting pounds of TNT to pounds of C-4 explosive) was used to calculate the charges for cutting round bars greater than 2 inches in diameter.

** Charge thicknesses were rounded to nearest common fraction. Actual thicknesses were 0.207 inch (± 3 percent).

Table XXIV. Summary of Explosive-Cutting Test Results on Steel Pipe

Test Shot	Dimension (in.) Outside Diameter	Inside Diameter	Thickness	Cross-Sectional Area (in.)^2	Explosive Charge: Weight (lb) Calculated by Formula $P = \frac{3/8\,A}{1.34}$	Actual	Percentage of Formula to Actual	Kind of Explosive	Dimension (in.) Width	Thickness	Length	Result
121	2.375	1.503	0.436	2.66	0.75	0.27	36.00	Paste[(a)]	7/8	1/2	6-3/10	Charge made 1/4-inch depression in pipe and spalled the inside but did not break it.
122	2.375	1.503	0.436	2.66	0.75	0.38	50.66	Paste[(a)]	1-3/4	1/2	6-3/10	Same results as in test shot 121 with 3/8-inch depression on one side of pipe.
123	2.375	1.503	0.436	2.66	0.75	0.56	74.66	Paste[(b)]	2-3/4	7/8	5	Complete cut.
124	2.375	1.503	0.436	2.66	0.75	0.45	60.00	Paste[(b)]	2	7/8	4-1/4	Complete cut
125	2.375	1.503	0.426	2.66	0.75	0.38	50.66	Paste[(c)]	2-1/4	7/8	3	Incomplete cut, charge was too short to break pipe by major cross fracture.

Notes (a) The charge was placed around the entire circumference of the pipe and primed with a T-6 electric blasting cap.

(b) The charge was placed along one side of the pipe and primed at one end to produce a cross fracture in the pipe at the end of the charge opposite the point of initiation.

(c) Same charge placement procedure as described in note (b), but the charge was center primed with a T-6 cap vertically embedded in the explosive.

Table XXV. Summary of Linear Shaped Charge Test Results on Steel Plates

Type of Charge	Characteristic of Linear Shaped Charge: Dimension (in.) Length	Width	Thickness	Explosive Charge: Weight (lb)	Length (in.)	Width (in.)	Overall Height (in.)	Height above Liner (in.)	Standoff from Target (in.)	Priming	Cutting Effect on Steel (in.) Depth	Width	Length
DM-19	8	9-1/16	3/16	19.80	8	9-1/16	10-1/2	5	10	Center	3-1/4	4-1/2	10
DM-19	8	9-1/16	3/16	19.80	8	9-1/16	10-1/2	5	10	End	4-3/4	4-1/4	11
DM-19	8	9-1/16	3/16	19.80	8	9-1/16	10-1/2	5	10	Center	4	4-1/4	11-1/2
DM-19	8	9-1/16	3/16	19.80	8	9-1/16	10-1/2	5	10	Center	4-1/2	4-3/4	12
Two DM-19	16	18-1/8	3/16	39.60	16	18-1/8	10-1/2	5	10	End*	5	5	19-1/2
Two DM-19	16	18-1/8	3/16	39.60	16	18-1/8	10-1/2	5	10	End*	5	5	20-1/2
Improvised	8-1/8	4-7/16	3/16	5.02	8	4-1/2	5	3	4	Center	3-1/2	3-1/2	11-1/2
Improvised	8-1/8	4-7/16	3/16	5.02	8	4-1/2	5	3	4	End	4	4-1/4	11
Improvised	8	6-3/8	1/8	7.55	8	6-1/2	6	3	6	Center	2-7/8	4-3/4	11-3/4
Improvised	8	6-3/8	1/8	7.50	8	6-1/2	6	3	6	End	4-1/4	4	11
Improvised	8	6-3/8	3/16	7.44	8	6-1/2	6	3	6	Center	3-3/8	5	12-1/2
Improvised	8	6-3/8	3/16	7.45	8	6-1/2	6	3	6	End	4-1/2	4-1/2	11-1/4
Improvised	8	6-1/2	3/16	7.80	8	6-1/2	6	3	6	End	3-7/8	4-1/4	12
Improvised	8	6-1/2	3/16	7.80	8	6-1/2	6	3	6	Center	3-3/8	4-1/2	14

* Denotes two charges end to end.

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13 ABSTRACT This report covers an experimental program in which new techniques for explosive demolition of structural steel shapes were developed and evaluated in connection with the examination of current U. S. Army methods of steel cutting with high-explosive charges. Report concludes: (a) Both charge width and charge thickness have significant effects on the steel-cutting efficiency of contact explosive charges; (b) the point of charge initiation does not significantly affect the shattering power of contact explosive charges on steel; (c) a 3:1 ratio of charge width to charge thickness is optimum for contact explosive charges calculated to cut structural steel in thicknesses of 3 inches or less; (d) the formula $C_T = 1/2\ S_T$ $C_W = 3\ C_T$ is more accurate and efficient than the U. S. Army formula $P = \frac{3/8\ A}{1.34}$ for calculation of contact charges of Composition C-4, paste, and EL506A-5 Detasheet explosives to cut structural steel; (e) Composition C-4, paste, and EL506A-5 Detasheet explosives were equally effective as contact charges for cutting structural steel; because of its variable density, paste explosive was less effective than Composition C-4 explosive for cutting round steel bars; (f) the optimum offsets between linear contact charges emplaced to cut from both sides, for reliable explosive demolition of steel beams, are the alignment of the edge of one charge opposite the center of the charge on the other side of beams with steel thicknesses of less than 2 inches, and the alignment of the edge of one charge opposite the edge of the charge on the other side of beams with steel thicknesses of 2 inches or more; (g) the detonating cord firing system is more reliable than electric blasting caps in series circuits for simultaneous detonation of multiple contact charges used in the explosive demolition of steel beams; (h) the diamond charge technique is more effective and dependable than either the cross-fracture or dual-offset method for explosive cutting of steel bars.

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Cross-fracture split						
Spall damage						
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