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NAVORD REPORT 2753

THE EFFECT OF THE STEEL CASE ON THE AIR BLAST FROM HIGH EXPLOSIVES

19 FEBRUARY 1953

U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

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NAVORD Report 2753

THE EFFECT OF THE STEEL CASE ON THE AIR BLAST FROM HIGH EXPLOSIVES

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ABSTRACT: The formula developed by U. Fano of the Ballistic Research Laboratories has been revised by new theoretical and experimental considerations so as to give more reasonable predictions of the air blast from steel cased charges.

By the use of the same experimental data which was available to Fano plus new data on bare charges, it has been found that the ratios of the effective bare charge weights of the cased charges to the actual charge weights as calculated by the original Fano formula were about two-thirds as large as the proper experimental values.

Of the three revised formulae developed for finding bare charge equivalent weight, W', the expression which fits experimental data best is

$$\frac{W'}{W} = \frac{1 + \frac{M}{C}\left(1 - M'\right)}{1 + \frac{M}{C}}.$$

where $\frac{W'}{W}$ is the ratio of the bare charge equivalent weight to the actual charge weight and $\frac{M}{C}$ is the case to charge weight ratio; M' is equal to $\frac{M}{C}$ for all weapons with a metal weight to charge weight ratio less than one. For all values of $\frac{M}{C}$ greater than one use M' equal to one.

All the expressions developed correlate with positive impulse. To obtain results that correlate with peak pressure the right side of the above formula is multiplied by 1.19.

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Up until recently a formula derived shortly after the war by U. Fano of the Ballistic Research Laboratories to predict the effect of the bomb case on air blast has been accepted. Experiments conducted at the Ballistic Research Laboratories and this Laboratory have, within the past year, raised the question as to the applicability of the Fano formula as a means of predicting blast effects for cased charges from data measured on bare charges. Since most explosives comparison work has been done on bare charges, the implications of the failure of this formula are extremely important.

The work described in this report, although not completed, presents revised equations based on both experimental and theoretical considerations which enable a more reasonable prediction of air blast parameters from steel cased weapons. This work was performed under NOL task Re2c-2-1.

The author wishes to acknowledge the work of Martha J. Bengston and Roy W. Huff for their help in analysis and computations.

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Captain, USN
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By direction

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I. INTRODUCTION

1. All weapons when finally used have some kind of a cover or case, if for no other reason than to make shipping and handling of the explosive charge safer and easier. Heavier cases are used when greater fragmentation damage is desired. Still heavier cases are used when it is necessary that the weapon penetrate the target without breaking up. In all these weapons no matter how heavy and strong the case is made, the explosion of the weapon produces air blast. The amount of this air blast should be known for the assessment of the value of the weapon in comparison with others of different design and in the assessment of a weapon's value against a specific target.

2. It is the purpose of this report to revise the formula developed by Fano in reference (a) on the basis of new experimental data and on the bases of a new treatment of old World War II data and some new theoretical ideas on the partition of the energy of detonation between air blast and fragmentation.

II. DERIVATION OF FANO FORMULA AND COMPARISON OF RESULTS WITH EXPERIMENT

3. The Fano formula has been developed by the extension of the work of Gurney, reference (b), who considered the kinetic energy at the time of rupture as being made up of the kinetic energy of the explosion product gases and the kinetic energy of the case. If one considers a unit length of cased cylindrical charge the kinetic energy relation at the time of rupture can be written down as follows:

$$EC = \frac{1}{2} MV^2 + \frac{1}{2}\left(\frac{1}{2}\ CV^2\right) \qquad (1)$$

where E is the total kinetic energy per unit weight
C is the weight of charge or weight of gases prior to rupture of case
M is the weight of metal case per unit length of cylindrical cased charge
V is the velocity of fragments at time of rupture.

It is assumed that the distribution of the velocities of the gas molecules at the time of rupture is not uniform, being zero in the center and V at the metal - gas interface. The $\frac{1}{2}$ in front of the $\left(\frac{1}{2}CV^2\right)$ is used to take this assumption into account. Solving equation (1) for E and substituting fragment velocity data for V, Gurney found that E was about 80% of the total detonation energy. By taking the ratio of the kinetic energy of the fragments $\left(\frac{1}{2}MV^2\right)$ to the total kinetic energy, equation (1), Fano obtained the fraction of the total kinetic energy going into the fragments to be

$$\frac{1}{1+\frac{C}{2M}} \tag{2}$$

The fraction of the kinetic energy belonging to the gases after the case has burst is thus

$$1-\frac{1}{1+\frac{C}{2M}}=\frac{1}{1+\frac{2M}{C}} \tag{3}$$

This was multiplied by 0.8 to account for the fraction of the total detonation energy belonging to the gases and case as kinetic energy at the time of rupture of the case. The 20% of the total energy remaining in the gases as potential energy plus the amount of kinetic energy remaining in the gases at the time of rupture is probably mostly spent in the formation of the blast.

4. The equivalent bare charge weight, W', relative to the amount of explosive, W, in the cased charge was given as

$$\frac{W'}{W}=0.2+\frac{0.8}{1+\frac{2M}{C}} \tag{4}$$

The above equation herein referred to as Fano's formula was checked roughly in reference (a) by showing that when the distances from all types of bombs are reduced by the cube root of W', their equivalent bare charge weight, the data fall approximately on a single curve for peak pressure. The same was found to be true for positive impulse data when the positive impulse value as well as the distance was reduced by the cube root of W' in accordance with the scaling laws. This showed that the Fano formula predicted the relative effect of one case with respect to another but failed to show how W' compared with actual bare charge data. The effective bare charge weights predicted by this formula were low by as much as 40 per cent from the subsequently experimentally determined values.

5. From the data taken from the appendix in reference (a) the effective bare charge replacement value, W', Tables I and II, was determined by methods described in detail in reference (c). Briefly these involved the scaling up of the theoretical free air bare charge data for cast TNT given by Kirkwood and Brinkley in reference (d) as corrected for ground reflection by experimental data obtained in the far Mach region reference (e). From a study of the ERL cased charge experiments the reflection coefficient was determined to be 1.5 (reference (e)). Reflection coefficient is defined as the ratio of the weight of a charge in free air to the weight of a charge fired near a reflecting surface that will give the same air blast effect (peak pressure or positive impulse) at a given distance.

6. From these results the discrepancy between the Fano formula and the experimental work applying the scaling laws can be seen in the following table:

	$\frac{W'}{W} = 0.2 + \frac{0.8}{1 + \frac{2}{C}\frac{M}{}}$ (Fano Formula)	Mean $\frac{W'}{W}$ Experimental Work and Scaling Laws	
Light Cased Bombs	0.74	1.09	Peak Pressure
		0.94	Positive Impulse
General Purpose Bombs	0.58	0.91	Peak Pressure
		0.80	Positive Impulse
Semi Armor Piercing Bombs	0.38	0.53	Peak Pressure
		0.45	Positive Impulse

The Fano equation (4) is plotted in Fig. 1.

7. In the Naval Ordnance Laboratory's 100-pound GP bomb experiment, reference (c), $\frac{W'}{W}$ is calculated to be 0.81 for positive impulse and 1.03 for peak pressure which is close to results of 0.80 for positive impulse and 0.91 for peak pressure as calculated from BRL data, see also Tables I and II. This data tends to show the steel case effect for HBX-1 is not far different from TNT loaded weapons.

III. DERIVATION OF NEW FORMULAE AND COMPARISON OF RESULTS WITH EXPERIMENT

8. An equation was developed for $\frac{W'}{W}$ resulting in close agreement with experiment by making the reasonable assumption that nearly all the gas molecules at the time of rupture of the case travel in a cylindrical shell with a velocity V equal to the fragment velocity. When this assumption was put into equation (1) the kinetic energy equation at the time of rupture became

$$EC = \frac{1}{2} MV^2 + \frac{1}{2} CV^2 \qquad (5)$$

which yielded a $\frac{W'}{W}$ bare charge equivalent to actual charge weight ratio of

$$\frac{W'}{W} = 0.2 + \frac{0.8}{1 + \frac{M}{C}} \qquad (6)$$

This equation improves the agreement with experiment as shown in the table below

	$\frac{W'}{W} = 0.2 + \frac{0.8}{1 + \frac{M}{C}}$ (Fano Formula modified for gas molecule velocities)	Mean $\frac{W'}{W}$ Experimental work and scaling laws	
Light Cased Bombs	0.85	1.09	Peak Pressure
		0.94	Positive Impulse
General Purpose Bombs	0.74	0.91	Peak Pressure
		0.80	Positive Impulse
Semi Armor Piercing Bombs	0.50	0.53	Peak Pressure
		0.45	Positive Impulse

Equation (6) is plotted on Fig. 1.

9. It has been possible to recalculate, E, in equation (5) by making use of the following recent fragmentation data informally supplied by A. D. Solem of the Detonation Division, Explosives Research Department of this Laboratory:

Fragment Velocity, V = 3678 ft/sec.
Charge to Case Weight Ratio, $\frac{C}{M} = 0.358$.
Total Detonation Energy (Cast TNT) = 1080 cal/gm.

The calculation gave a value for E, total kinetic energy of the fragments and explosion products at the time of rupture, of 569 calories per gram, or 53 per cent of the total detonation energy. If this factor of 53 per cent is used in equation (6) it becomes:

$$\frac{W'}{W} = 0.47 + \frac{0.53}{1 + \frac{M}{C}} \qquad (7)$$

The agreement of equation (7) with experimental results is shown below

	$\frac{W'}{W} = 0.47 + \frac{0.53}{1 + \frac{M}{C}}$ (Equation (7))	Mean $\frac{W'}{W}$ Experimental Work and Scaling Laws	
Light Cased Bombs	0.90	1.09	Peak Pressure
		0.94	Positive Impulse
General Purpose Bombs	0.81	0.91	Peak Pressure
		0.80	Positive Impulse
Semi Armor Piercing Bombs	0.67	0.53	Peak Pressure
		0.45	Positive Impulse

Equation (7) is plotted in Fig. 1.

10. An empirical formula that fits experimental impulse data closely is as follows

$$\frac{W'}{W} = \frac{1 + \frac{M}{C}(1 - M')}{1 + \frac{M}{C}} \qquad (8)$$

M' is equal to $\frac{M}{C}$ for all weapons with a metal weight to charge weight ratio less than one. For all values of $\frac{M}{C}$ greater than one use M' equal to one. For example, M' is equal to 0.23 for light cased weapons and one for semi armor piercing weapons. Multiply equation (8) by 1.19 to obtain $\frac{W'}{W}$ for peak pressure. This in essence implies that the percentage of detonation energy converted into kinetic energy is directly proportional to the percentage of metal weight up to a case having an $\frac{M}{C}$ ratio of one or greater.

The table below shows the agreement of equation (8) with the values obtained from experiment and the scaling laws.

	$\frac{W'}{W} = \frac{1 + \frac{M}{C}(1 - M')}{1 + \frac{M}{C}}$ (Equation (8))	Mean $\frac{W'}{W}$ Experimental Work and Scaling Laws	
Light Cased Bombs	1.14	1.09	Peak Pressure
	0.96	0.94	Positive Impulse
General Purpose Bombs	0.95	0.91	Peak Pressure
	0.80	0.80	Positive Impulse
Semi Armor Piercing Bombs	0.46	0.53	Peak Pressure
	0.38	0.45	Positive Impulse

Equation (8) is plotted on Fig. 1 showing the difference between it and the Fano equation.

11. Figures 2, 3, 4, and 5 are plots of peak pressure vs reduced radial distance in which the bomb data tabulated in Table I is compared with bare charge data. The source of this bare charge data is mentioned earlier in this report. The bomb data has been scaled by using the cube root of the effective bare charge weight as calculated from the four equations discussed in this report. As can be seen from the graphs the bomb peak pressure data scales poorly for all equations except equation (8) as modified by the factor 1.19 for peak pressure. Figures 6, 7, 8, and 9 are plots of reduced positive impulse vs reduced radial distance in which the bomb data tabulated in Table II are compared with experimental bare charge data. The bomb data has been scaled by use of the cube root of the effective bare charge weight as calculated by the four equations discussed in this report. The bomb positive impulse data scales well for all equations except the Fano equation, Fig. 6 as can be seen from the graphs.

IV. CONCLUSIONS

12. It is concluded that the formulae developed from kinetic energy considerations at the time of rupture correlate best with positive impulse data. Therefore to predict positive impulse results the new formulae developed in this report can be used without modification. The experimental data indicate that to predict peak pressure results the formulae should be multiplied by the factor 1.19.

13. The table below shows the formulae to use that best agree with experimental work and scaling law results for predicting $\frac{W'}{W}$.

Case Type	*Light Case	*General Purpose	*Semi Armor Piercing
Positive Impulse	$\frac{W'}{W} = \frac{1 + \frac{M}{C}(1 - M')}{1 + \frac{M}{C}}$	$\frac{W'}{W} = \frac{1 + \frac{M}{C}(1 - M')}{1 + \frac{M}{C}}$	$\frac{W'}{W} = 0.2 + \frac{0.8}{1 + \frac{M}{C}}$
Peak Pressure	$\frac{W'}{W} = 1.19\left[\frac{1 + \frac{M}{C}(1 - M')}{1 + \frac{M}{C}}\right]$	$\frac{W'}{W} = 1.19\left[\frac{1 + \frac{M}{C}(1 - M')}{1 + \frac{M}{C}}\right]$	$\frac{W'}{W} = 1.19\left[0.2 + \frac{0.8}{1 + \frac{M}{C}}\right]$

* Refers to the charge to total weight ratio in the regions of the present type weapons described by light case, general purpose and semi armor piercing.

REFERENCES

(a) Methods for Computing Data on the Terminal Ballistics of Bombs - II Estimation of the Air Blast; U. Fano, Ballistic Research Laboratories Report 524, Restricted.

(b) Initial Velocities of Fragments of Bombs, Shells and Grenades; R. W. Gurney, BRL Report 405.

(c) NAVORD Report 2474 - Air Blast Effectiveness of "100-pound" General Purpose Steel Cased Bomb as Measured by Piezoelectric and Indenter Gages; Robert R. Caforek, Confidential.

(d) Theoretical Blast Wave Curves for Cast TNT; Kirkwood and Brinkley, OSRD #5481, Confidential.

(e) NAVORD Report 2123 - Experimental Shock Wave Reflection Studies with Several Different Reflecting Surfaces; E. M. Fisher, Confidential

TABLE I

Peak Pressure Data From Steel Cased TNT Weapons

Weapon Description	Peak Pressure (psi)	Distance (ft)	C/W	Actual Weight of TNT (W)	Effective Bare Charge Weight TNT W'	$\frac{W'}{W}$
10,000 lb LC Bomb	2.95	384	0.82	7050	6300	0.89
4,000 lb LC Bomb	3.15	300	0.82	3362	3430	1.02
4,000 lb LC Bomb	6.23	211	0.82	3362	4265	1.27
4,000 lb LC Bomb	3.09	320	0.82	3362	3230	0.96
MK 6 Depth Charge	16.39	60	0.77	300	447	1.49
MK 6 Depth Charge	6.23	90	0.77	300	331	1.10
MK 6 Depth Charge	3.10	130	0.77	300	271	0.90
					Mean	1.09
2,000 lb GP Bomb	2.94	204.8	0.64	1117	940	0.84
2,000 lb GP Bomb	2.27	242.8	0.64	1117	895	0.80
2,000 lb GP Bomb	3.97	165.0	0.64	1117	869	0.78
1,000 lb GP Bomb	2.99	165.8	0.65	558	523	0.94
500 lb GP Bomb	3.05	129.7	0.65	267	265	0.99
500 lb GP Bomb	1.82	167.3	0.65	267	151	0.57
500 lb GP Bomb	12.94	59.7	0.65	267	312	1.17
500 lb GP Bomb	5.87	89.3	0.65	267	296	1.11
500 lb GP Bomb	3.01	129.6	0.65	267	257	0.96
100 lb GP Bomb	3.23	76.3	0.65	55	58.8	1.07
100 lb GP Bomb	2.02	97.9	0.65	55	43.7	0.79
					Mean	0.91
2,000 lb SAP Bomb	2.18	166.2	0.36	556	262	0.47
1,000 lb SAP Bomb	2.22	136.5	0.38	320	148	0.46
500 lb SAP Bomb	2.55	108.4	0.38	161	105	0.65
					Mean	0.53

Note: All weapons fired slightly above ground to avoid cratering.
C/W charge to weight ratio of cylindrical section of weapon.
W' is calculated by scaling up bare charge data.
Peak Pressure values are averages of a number of trials.

TABLE II

Positive Impulse Data From Steel Cased TNT Weapons

Weapon Description	Positive Impulse psi-ms	Distance (ft)	C/W	Actual Weight of TNT (W)	Effective Bare Charge Weight TNT W'	W'/W
10,000 lb LC Bomb	78.2	334	0.82	7050	6400	0.92
4,000 lb LC Bomb	55.1	300	0.82	3362	2760	0.82
4,000 lb LC Bomb	120.4	151.3	0.82	3362	3976	1.18
4,000 lb LC Bomb	62.2	300	0.82	3362	3180	0.95
4,000 lb LC Bomb	119.7	149.8	0.82	3362	3835	1.14
MK 6 Depth Charge	48.9	60.0	0.77	300	262	0.87
MK 6 Depth Charge	23.64	129.6	0.77	300	213	0.71
					Mean	0.94
2,000 lb GP Bomb	32.66	204.8	0.64	1117	688	0.62
2,000 lb GP Bomb	86.05	79.5	0.64	1117	996	0.89
2,000 lb GP Bomb	59.62	120.0	0.64	1117	848	0.76
1,000 lb GP Bomb	28.2	165.7	0.65	558	394	0.71
500 lb GP Bomb	25.02	129.7	0.65	267	232	0.87
500 lb GP Bomb	49.17	59.7	0.65	267	264	0.99
500 lb GP Bomb	20.50	129.7	0.65	267	168	0.63
100 lb GP Bomb	16.03	76.4	0.65	55	52.5	0.96
					Mean	0.80
2,000 lb SAP Bomb	20.12	163.2	0.36	556	228.0	0.41
2,000 lb SAP Bomb	11.93	297.2	0.36	556	270.0	0.49
					Mean	0.45

Note: All weapons fired slightly above ground to avoid cratering.
C/W charge to weight ratio of cylindrical section of weapon.
W' is calculated by scaling up bare charge data.
Positive impulse is an average of a number of trials.

FIG. I
COMPARISON OF EQUATIONS FOR FINDING THE EFFECTIVE BARE CHARGE WEIGHT OF A STEEL CASED WEAPON

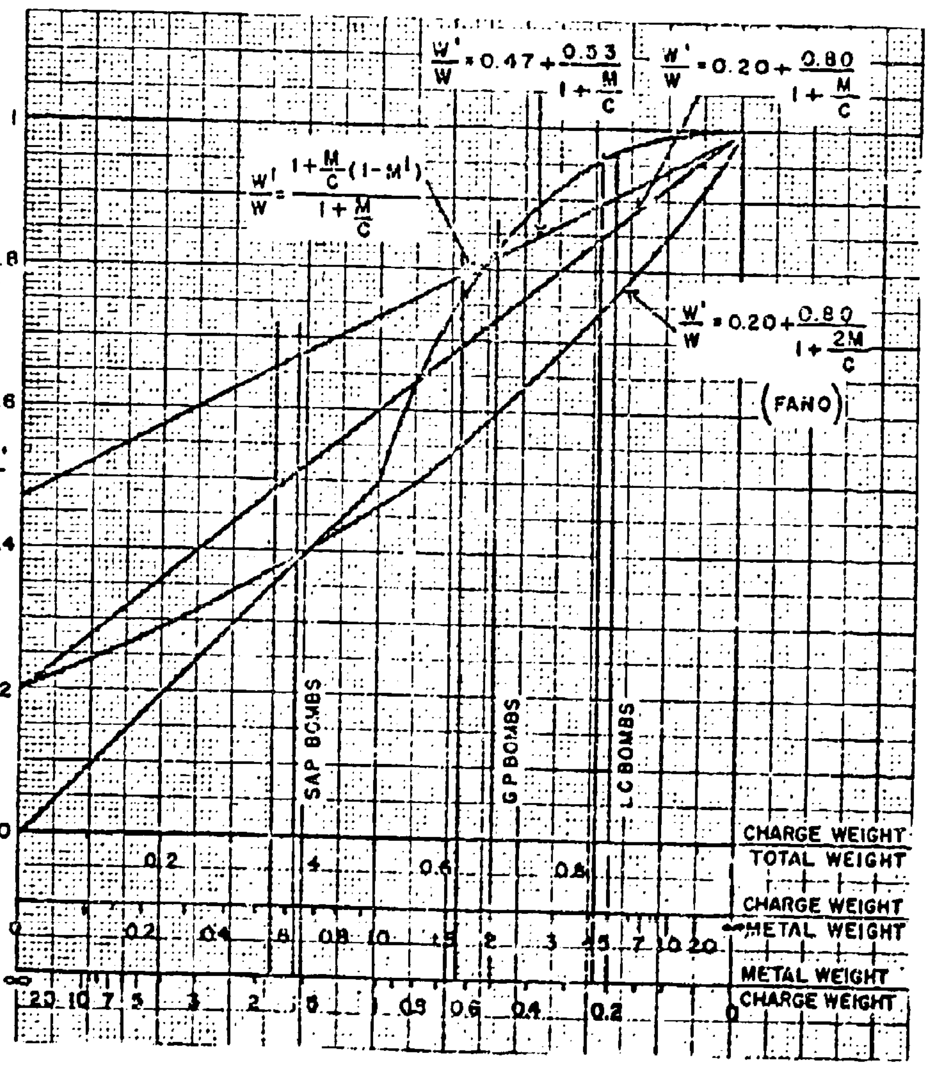


FIG. 2

PEAK PRESSURE VS REDUCED RADIAL DISTANCE FOR CAST TNT IN FAR MACH REGION

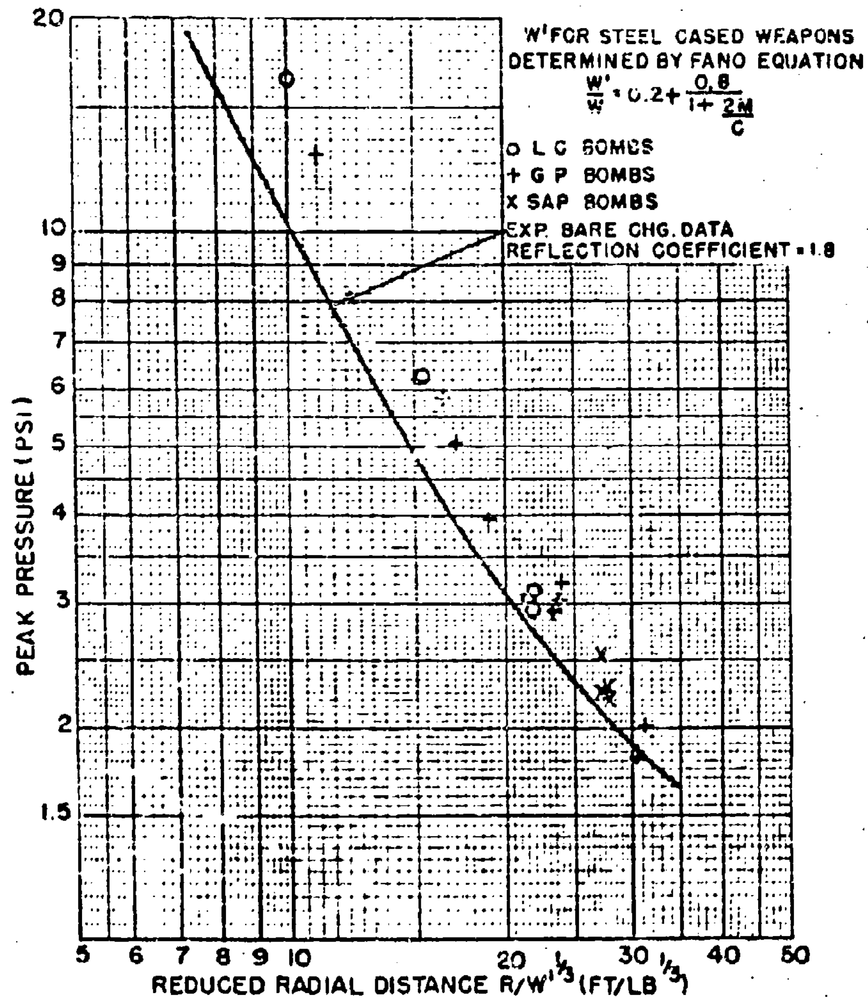


FIG. 3
PEAK PRESSURE VS REDUCED RADIAL DISTANCE
FOR CAST TNT IN FAR MACH REGION

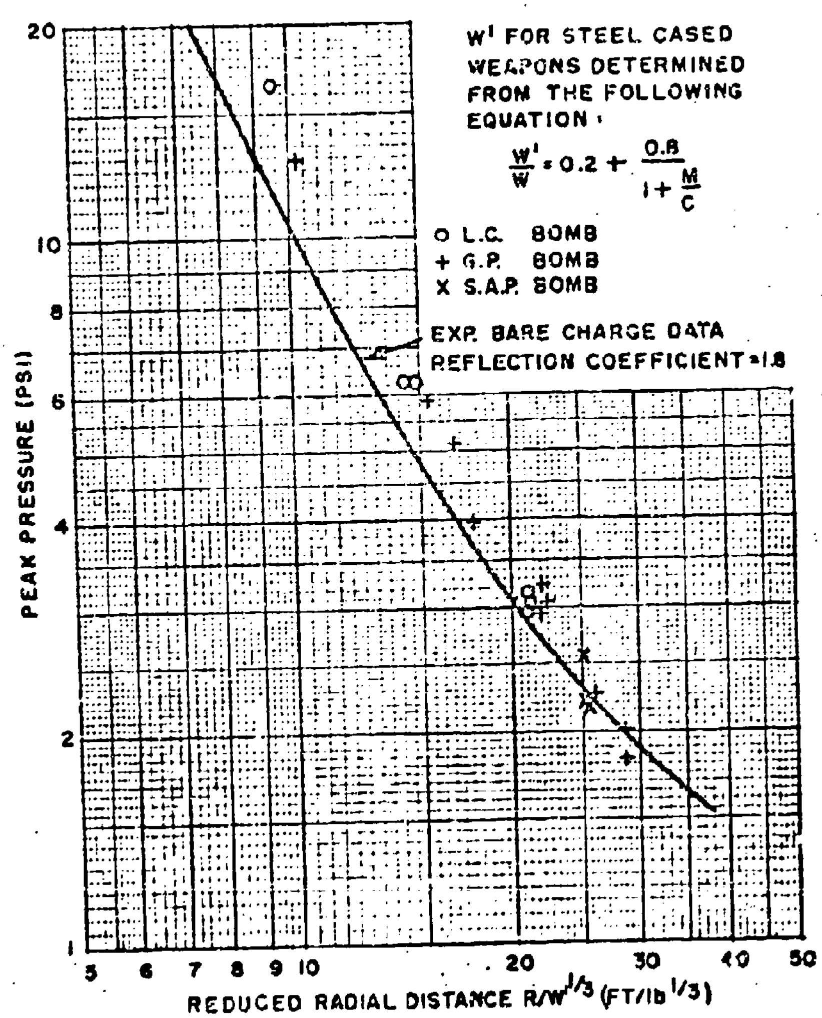


FIG. 4
PEAK PRESSURE VS REDUCED RADIAL DISTANCE
FOR CAST TNT IN FAR MACH REGION

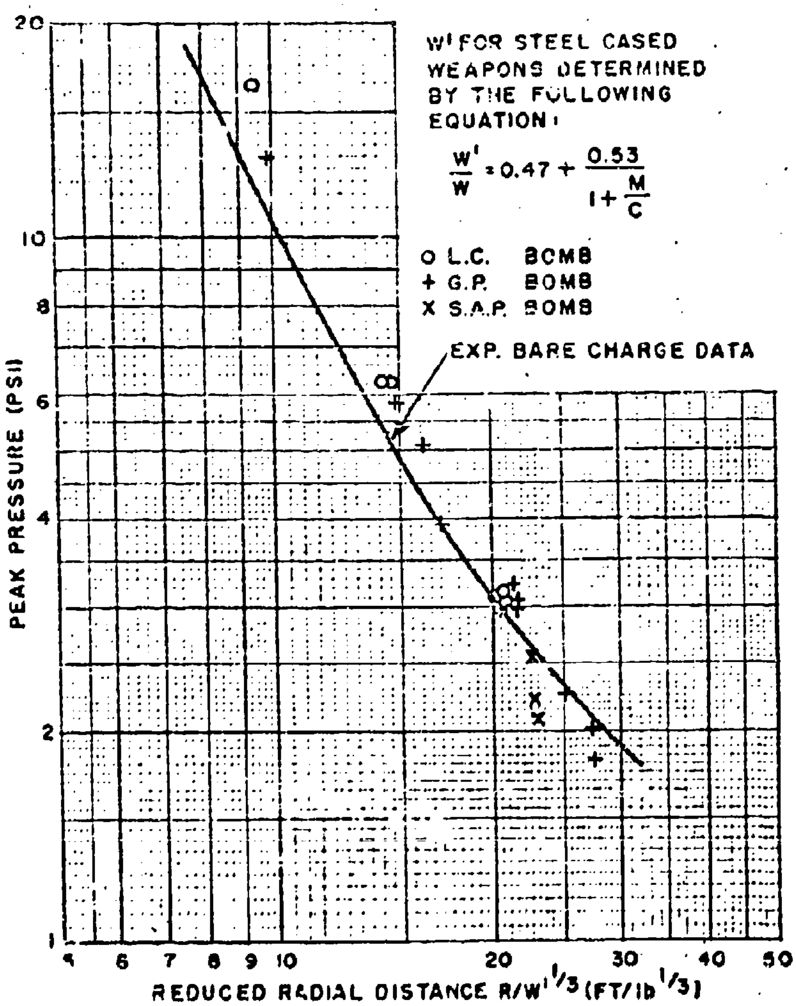


FIG. 5
PEAK PRESSURE VS REDUCED RADIAL DISTANCE
FOR CAST TNT IN FAR MACH REGION

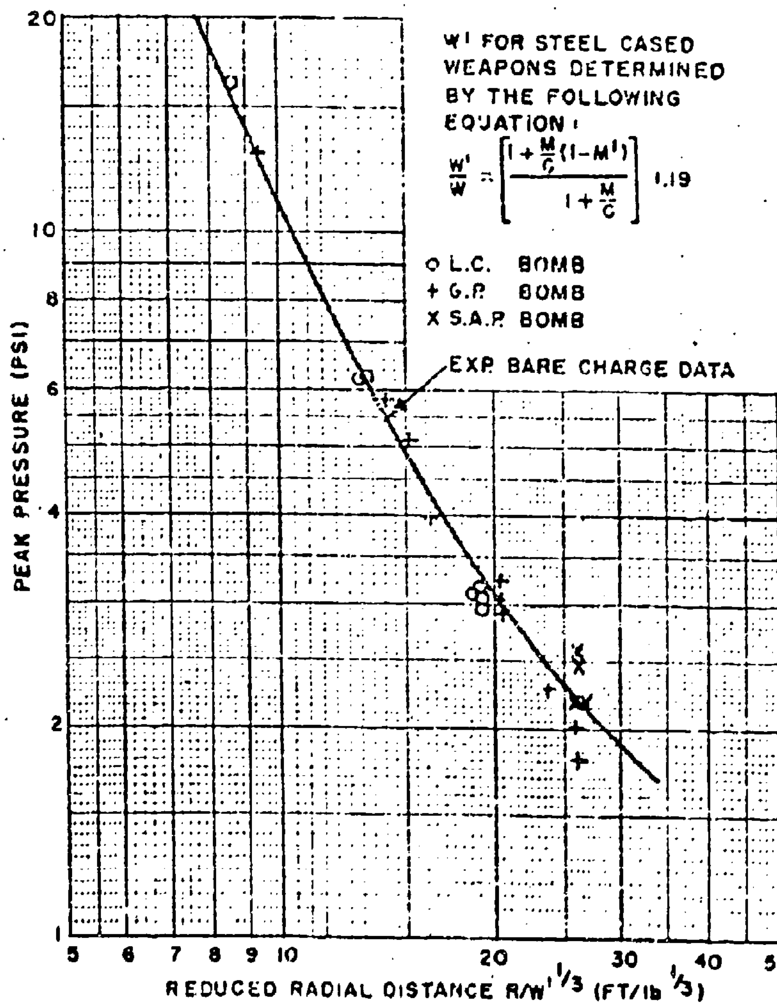


FIG. 6
REDUCED POSITIVE IMPULSE VS REDUCED RADIAL DISTANCE
FOR CAST TNT IN FAR MACH REGION

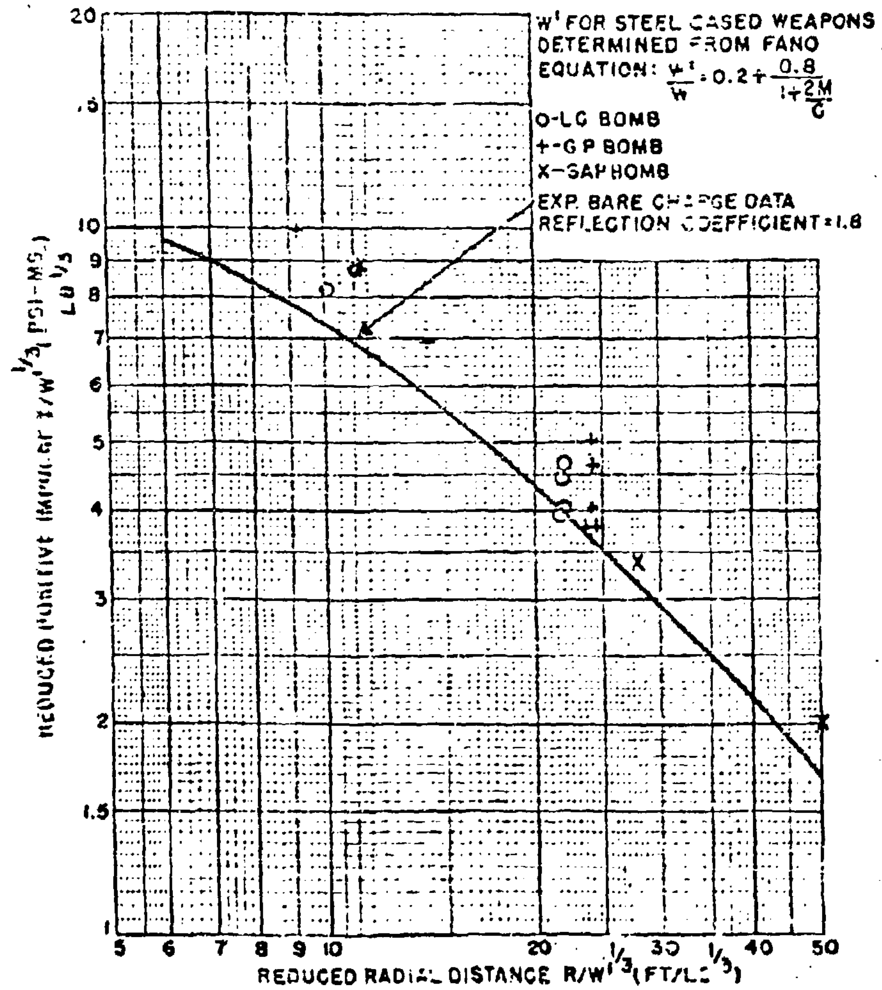


FIG. 7

REDUCED POSITIVE IMPULSE VS REDUCED RADIAL DISTANCE FOR CAST TNT IN FAR MACH REGION

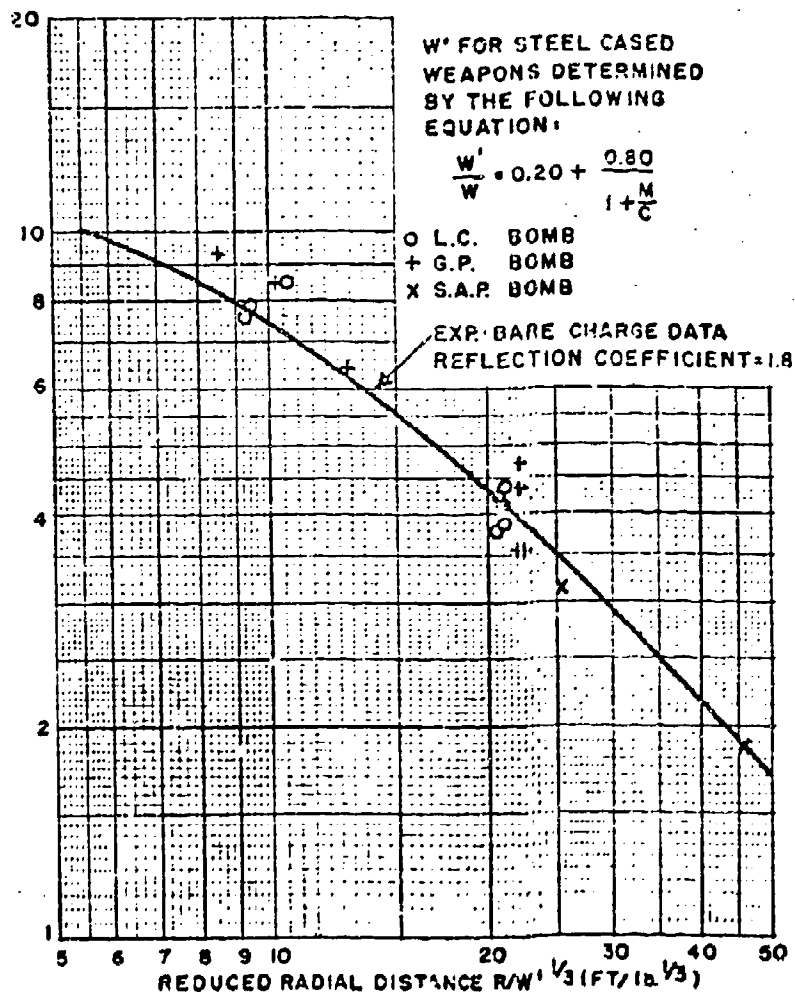


FIG. 8

REDUCED POSITIVE IMPULSE VS REDUCED RADIAL DISTANCE FOR CAST TNT IN FAR MACH REGION

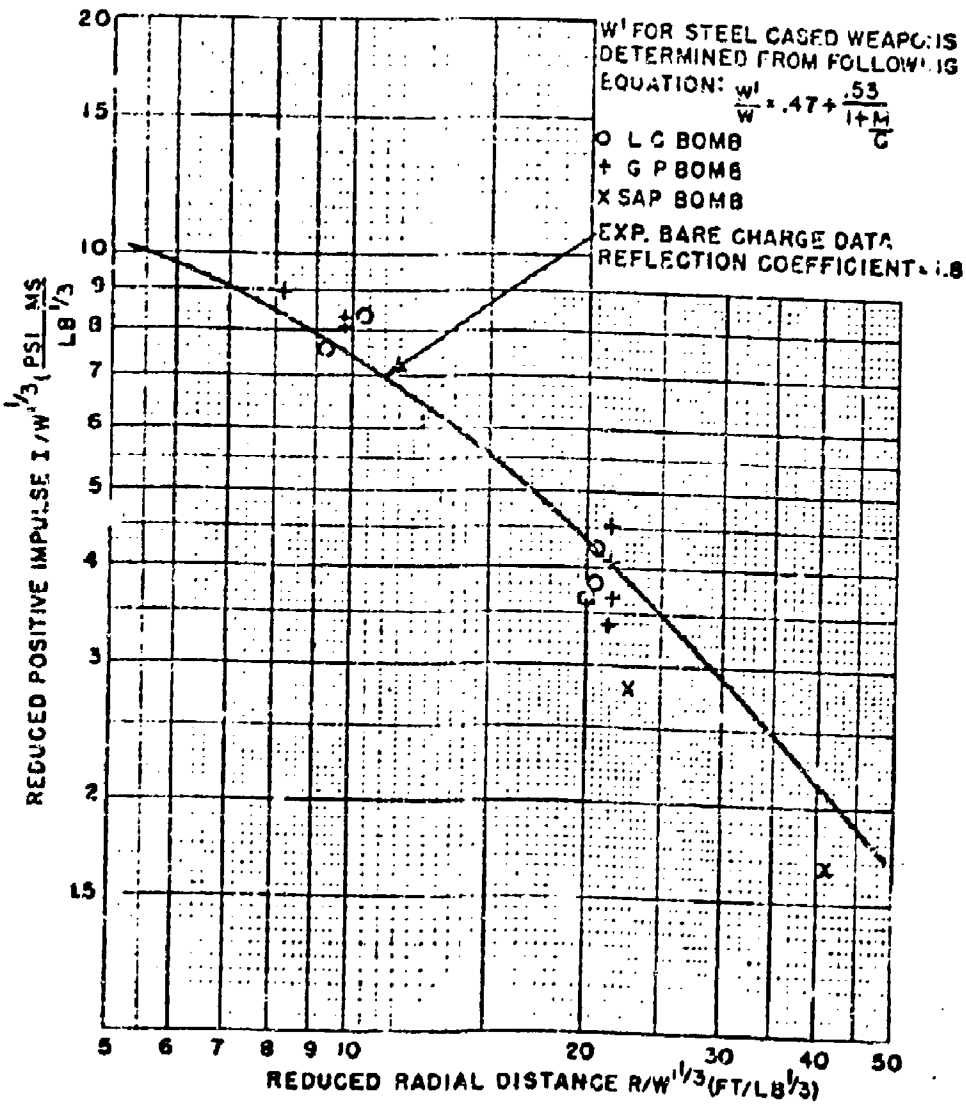
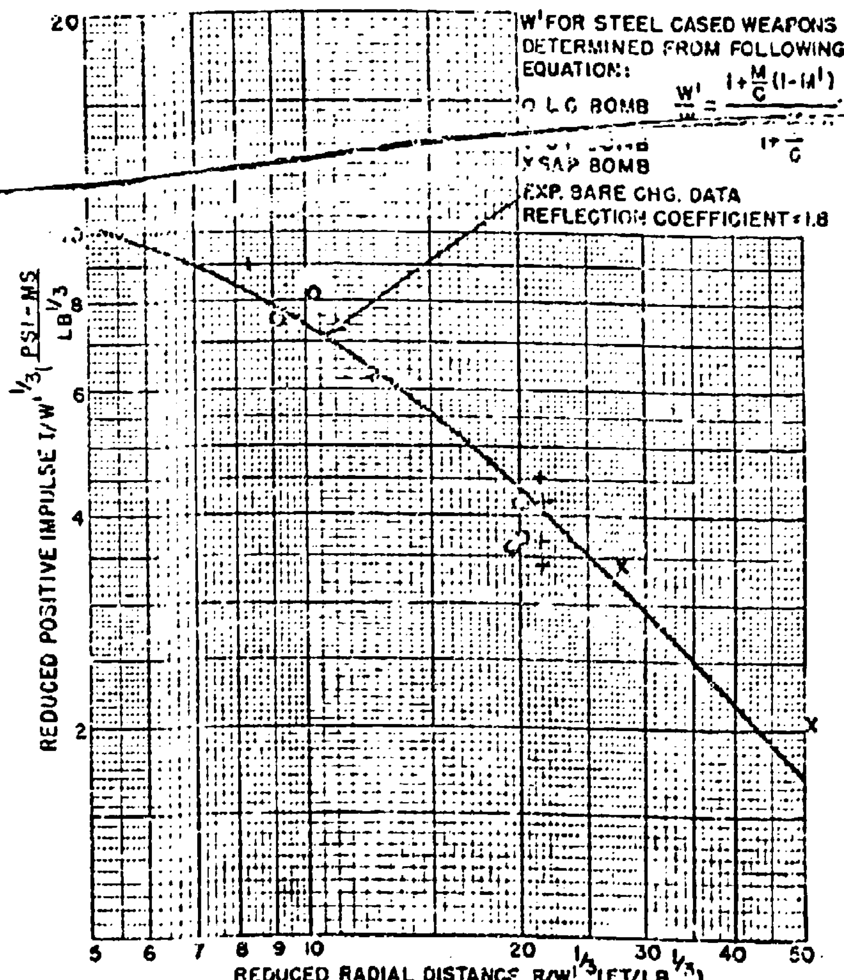


FIG. 9

REDUCED POSITIVE IMPULSE VS REDUCED RADIAL DISTANCE FOR CAST TNT IN FAR MACH REGION



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