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Division 2, National Defense Research Committee of the
Office of Scientific Research and Development

MONTHLY REPORT NO. AES-7 (OSRD NO. 4754)

AIR AND EARTH SHOCK

Volume 7. January 25 to February 25, 1945

A Compilation of Informal Reports Submitted in
Advance of Formal Reports

Pertinent Service Projects

OD-03 NO-267
NO-224

Copy No. 48

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Office of Scientific Research and Development

MONTHLY REPORT NO. AES-7 (OSRD NO. 4754)

AIR AND EARTH SHOCK

Volume 7. January 25 to February 25, 1945

A Compilation of Informal Reports Submitted in Advance of Formal Reports

Pertinent Service Projects

OD-03 NO-267

NO-224

Approved on March 5, 1945
for submission to the Committee

E B. Wilson Jr

E. B. Wilson, Jr., Chief
Division 2, NDRC
Effects of Impact and Explosion

The NDRC Technical Reports Section
for Armor and Ordnance edited
this report and prepared it for duplication.

Preface

This report is the seventh monthly report of Division 2, NDRC, on Air and Earth Shock, covering the period from January 25 to February 25, 1945. These monthly reports are compilations of informal reports submitted in advance of formal reports. In no case is it to be presumed that the work is complete or that the results reported are other than tentative.

The work described in this report is pertinent to the project designated by the War Department Liaison Officer as OD-03, and to the projects designated by the Navy Department Liaison Officer as NO-224 and NO-267. The work was performed under Contract OEMsr-260 with Princeton University and Contract OEMsr-569 with the Woods Hole Oceanographic Institution.

Arrangement is by project rather than by contract in order that all material pertinent to a particular phase of the work may appear together. These monthly AES reports are intended to give in some detail the results obtained during the preceding month by each of the contractors working on a particular project.

This bound copy is intended for the use only of those individuals and groups authorized to receive information about the activities of Division 2 in the entire field of Air and Earth Shock. It should not be shown to persons who are concerned with only a limited part of the work. Loose-leaf copies of the sections are available for distribution through liaison channels to those who have a legitimate interest in the results of work on individual projects.

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No. 80 to Director, Air Technical Service Command, Wright Field (TSESE-4I);

No. 81 to W. D. Kennedy, Woods Hole Oceanographic Institution;

No. 82 to H. L. Beckwith, Princeton University.

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Division 2, NDRC
Monthly Report AES-7 (OSRD-4754)
February 25, 1945

Project OD-03

ADVANCE RELEASE: This
information is tentative
and subject to revision.

Princeton University
W. Bleakney, Supervisor

AN EXPERIMENTAL DETERMINATION OF THE POINT OF CATCHUP OF THE RAREFACTION WAVE AND THE IMPULSE OF THE SHOCK WAVE IN A TUBE

by C. W. Lampson

Abstract

Experiments are reported here which show that:

(i) The impulse in the shock wave in a tube at the critical distance is very nearly proportional to the excess chamber pressure and can be calculated by considerations of the energy in the shock wave.

(ii) The length of expansion tube necessary to allow the rarefaction wave to catch the shock front and to produce a peaked shock wave can be found from a knowledge of the various wave velocities and is of the order of magnitude of fifteen times the compression-chamber length at the higher shock pressures.

1. Experimental setup

A series of experiments was made in order to check some of the results of a theoretical analysis of the properties of the shock wave developed in a tube from the bursting of a diaphragm. The main objectives were the determination of (i) the point of catchup of the rarefaction wave with the shock front and (ii) the impulse of the shock wave at the point of catchup.

The setup consisted of a standard calibration tube[1] of 3-in. diameter with the compression chamber reduced to a length of 7-7/16 in. by means of a tightly fitting wooden plug which occupied the remainder of the original 2-ft length. Sections of expansion tube were fitted in place to a total length of approximately 14 ft. Quartz gauges were fitted into ports in the side of the expansion chamber at distances from the diaphragm of 6 ft 10 in., 7 ft 10 in., 8 ft 10 in., and 9 ft 10 in., giving at these points the ratios of length of

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[1] For a description of the tube see G. T. Reynolds, A preliminary study of plane shock waves formed by bursting diaphragms in a tube, NDRC Report A-192 (OSRD No. 1519).

expansion chamber to compression chamber, L/L_c, of 11.0, 12.65, 14.25, and 15.86, respectively. The outputs of the quartz gauges were led through the customary padding condensers and preamplifiers to four DuMont 175A oscillographs modified to have a common single sweep and photographed by four Foth-Derby f/2.5 cameras.

The setup remained unchanged throughout the experiments except for the removal of 2 ft of expansion tube from the end between shots designated in Fig. 1 as (4) and (5) and a simultaneous reduction in sensitivity of the oscillographs by a factor of 2. Duplicate shots were made at every chamber pressure, but the results superimposed so perfectly on the oscillograms that only one of each pressure was measured and shown on the oscillogram sheet (Fig. 1). Three timing shots were taken, of which only one is shown. Comparison of the three showed a negligible shift in sweep speed with time.

The data for the seven shots shown in Fig. 1, together with certain derived quantities, are tabulated in Table I.

2. Definition of symbols used

Symbol	Unit	Definition
a_o	ft/sec	Velocity of sound
I	lb msec/in.²	Impulse in shock wave
L	ft	Length of expansion chamber
L_c	ft	Length of compression chamber
P_c	lb/in.²	Compression-chamber pressure
P_o	lb/in.²	Atmospheric pressure, hence initial pressure of air in expansion tube
P_s	lb/in.²	Excess pressure in shock wave
P_{cs}	lb/in.	$P_c - P_o$
w	--	P_c/P_o
y	--	$(P_s + P_o)/P_o$

3. General results

Examination of the records showed a severe vibration present in the records from channel I (see Fig. 1) which greatly reduced the accuracy of

Table I. Data for seven shots.

Shot	P_c (lb/in.²)	$\underline{w}$	$\underline{y}$	P_s (lb/in.²)
0	timing shot -- frequency 1000 cycle/sec			
1	8.9	1.607	1.27	3.85
2	14.8	2.01	1.41	6.00
3	19.1	2.30	1.50	7.40
4	29.5	3.01	1.70	10.20
5	39.8	3.71	1.87	12.80
6	49.4	4.36	2.00	14.70

the records, although the nature of the pressure-time curve is evident through the disturbance. This vibration has been observed before and is associated with the mounting of the gauge in the tube. Apparently this gauge was improperly mounted in some way so that the vibrations of the tube associated with diaphragm breakage were transmitted to the gauge or to the cable connecting the gauge to the preamplifier. The traces on channel IV at the higher pressures showed a flattening at the top of the record which can not be real since a peaked record was obtained at a lower pressure. It is believed that the preamplifier was being driven to cutoff on the peaks since the reduction in sensitivity was made in the amplifiers of the oscillograph which followed the preamplifier. The channel-IV oscillograms were discarded for impulse measurement for this reason and also because the removal of the end section of the tube resulted in a reflected rarefaction wave which reduced the area by an indeterminate amount.

4. Impulse measurements

The records were enlarged by a factor of 8 and traced on Kodatrace in order that an accurate measurement of the impulse could be made. The value of pressure for each trace was calculated from the known compression-chamber pressure according to published curves.[2/] Experiments have shown that the

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[2/] See Fig. 5 of Ref. 1.

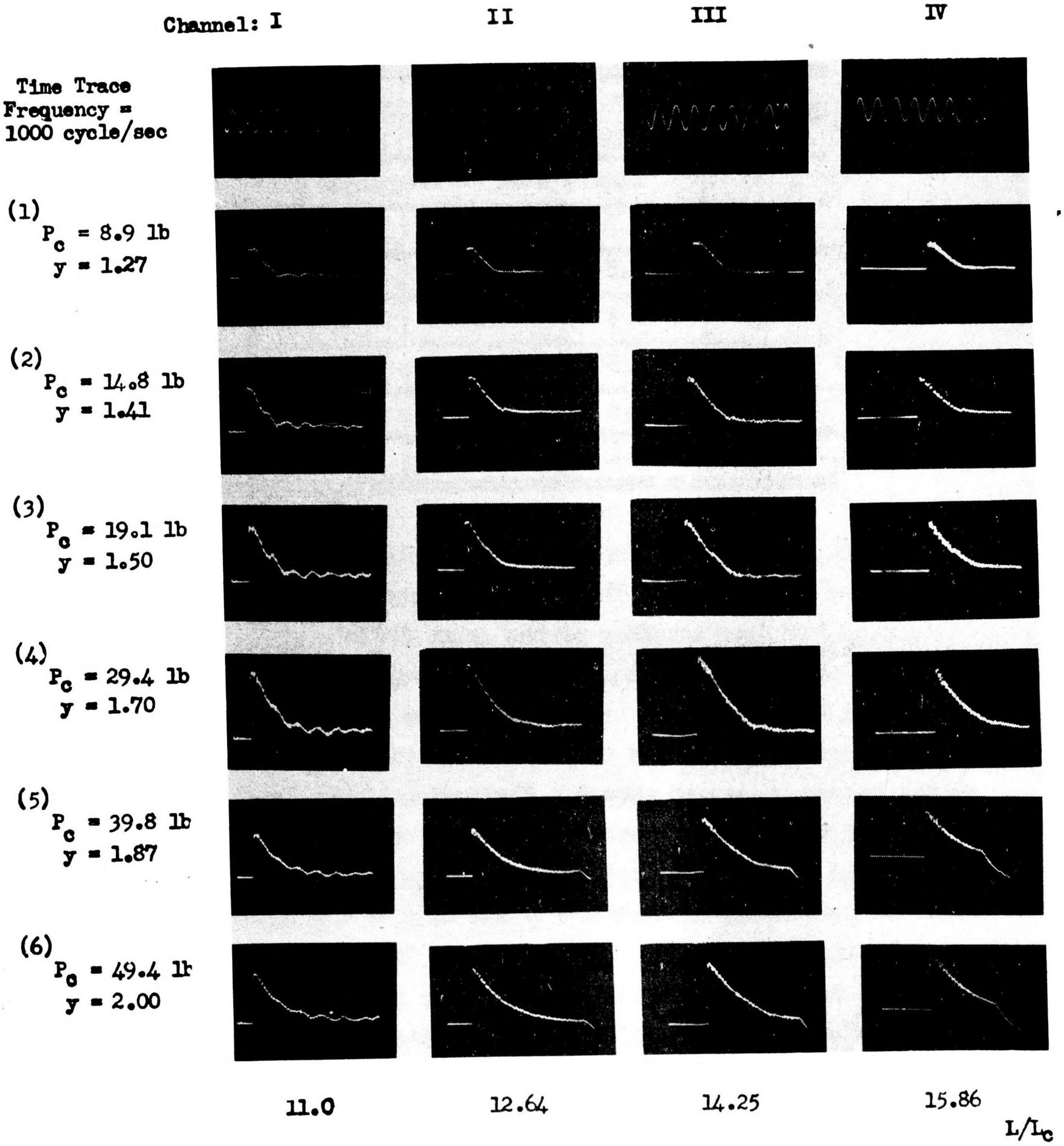

Fig. 1. Oscillograms showing shock wave in tube as a function of chamber pressure and distance from diaphragm.

amplitude of a step-shock changes by a negligible amount in traversing a distance of the order of magnitude used in these experiments; thus this procedure is probably more reliable than a prior gauge calibration would be except that the theoretical chamber pressure-shock amplitude curve is used in order to be consistent with the remainder of the analysis.

The results of the measurements of impulse on the respective traces are shown in Table II.

Table II. Impulse at various chamber pressures and ratios of expansion-chamber length to compression-chamber length.

Shot No.	P_{cs} (lb/in.^{2})	w - 1	y	P_s (lb/in.^{2})	Impulse I (lb msec/in.^{2})			
					At distance ratio L/L_c =			
					11.0	12.65	14.25	15.86
1	8.9	0.607	1.27	3.95	5.65	5.4	4.76	4.75
2	14.8	1.01	1.41	6.00	8.58	8.8	8.59	--
3	19.1	1.30	1.50	7.40	11.20	11.9	10.52	10.3
4	29.5	2.01	1.70	10.20	16.0	18.1	17.8	15.4
5	39.8	2.71	1.87	12.80	19.3	22.5	20.8	--
6	49.4	3.36	2.00	14.70	22.5	28.4	27.7	--

In Fig. 2 the quantity Ia_o/P_oL_c is plotted as a function of w - 1 (here I is in pound seconds per square inch) together with a curve computed from considerations of conservation of energy. The derivation of this curve will be published separately. The ordinate in this plot Ia_o/P_oL_c is a dimensionless quantity the values for which are obtained by multiplying each impulse in Table II by the factor a_o/P_oL_c which is equal to 0.1195×10^3 (in.^{2}/lb sec) in this case.

The points that are known to be at the catchup distance are solid circles. Other points are open circles, except that the less reliable values from channel I, which had gauge vibration, are marked as open squares.

5. Determination of the point of catchup

The location of the point of catchup is slightly indefinite, chiefly because the width of the gauge is an appreciable fraction of the initial

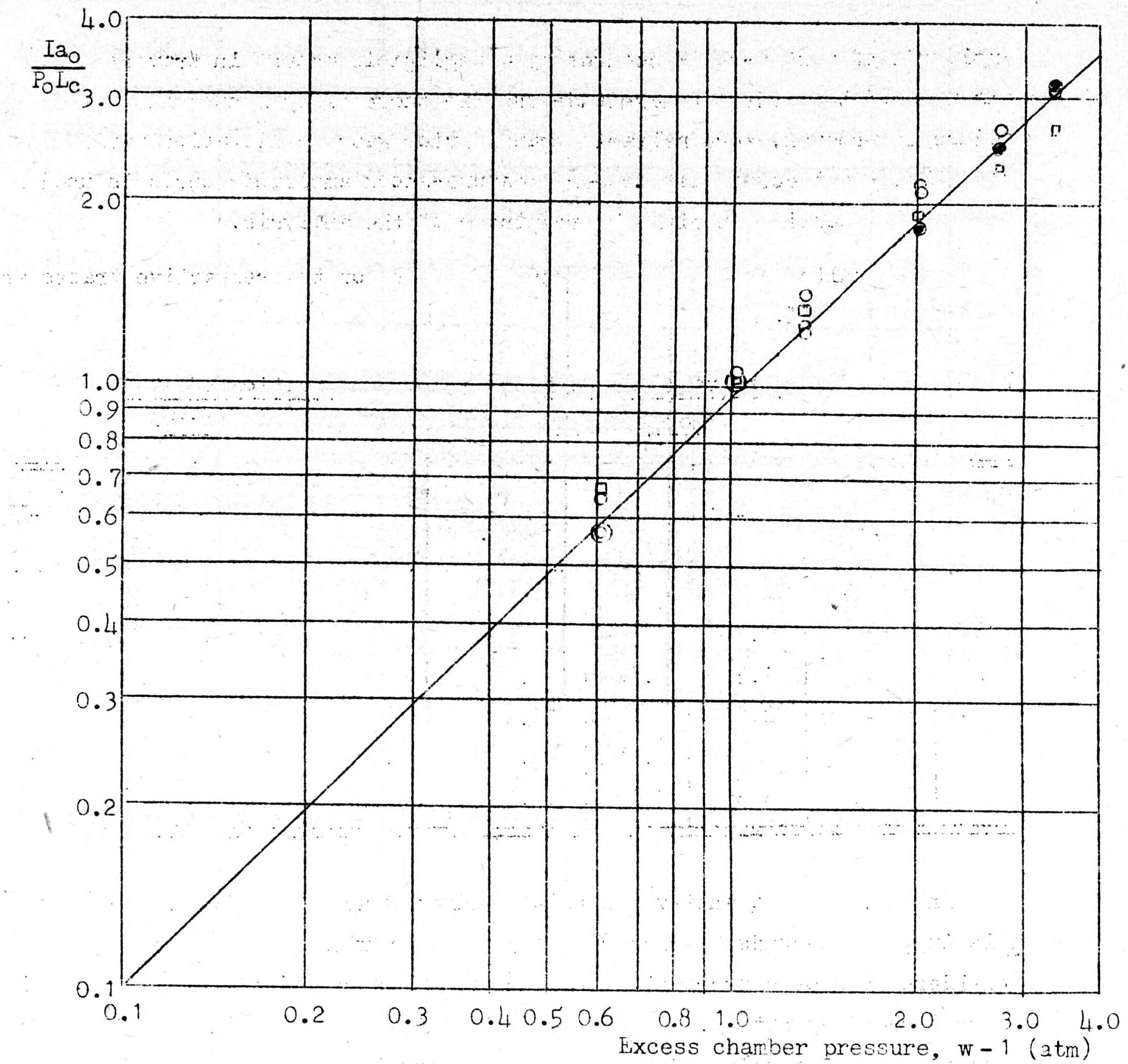

Fig. 2. Impulse in shock wave as a function of the compression-chamber pressure in excess of atmospheric.

———, calculated from considerations of conservation of energy

○, experimental points

●, impulse at points of catchup

□, impulse from channel I with vibrations

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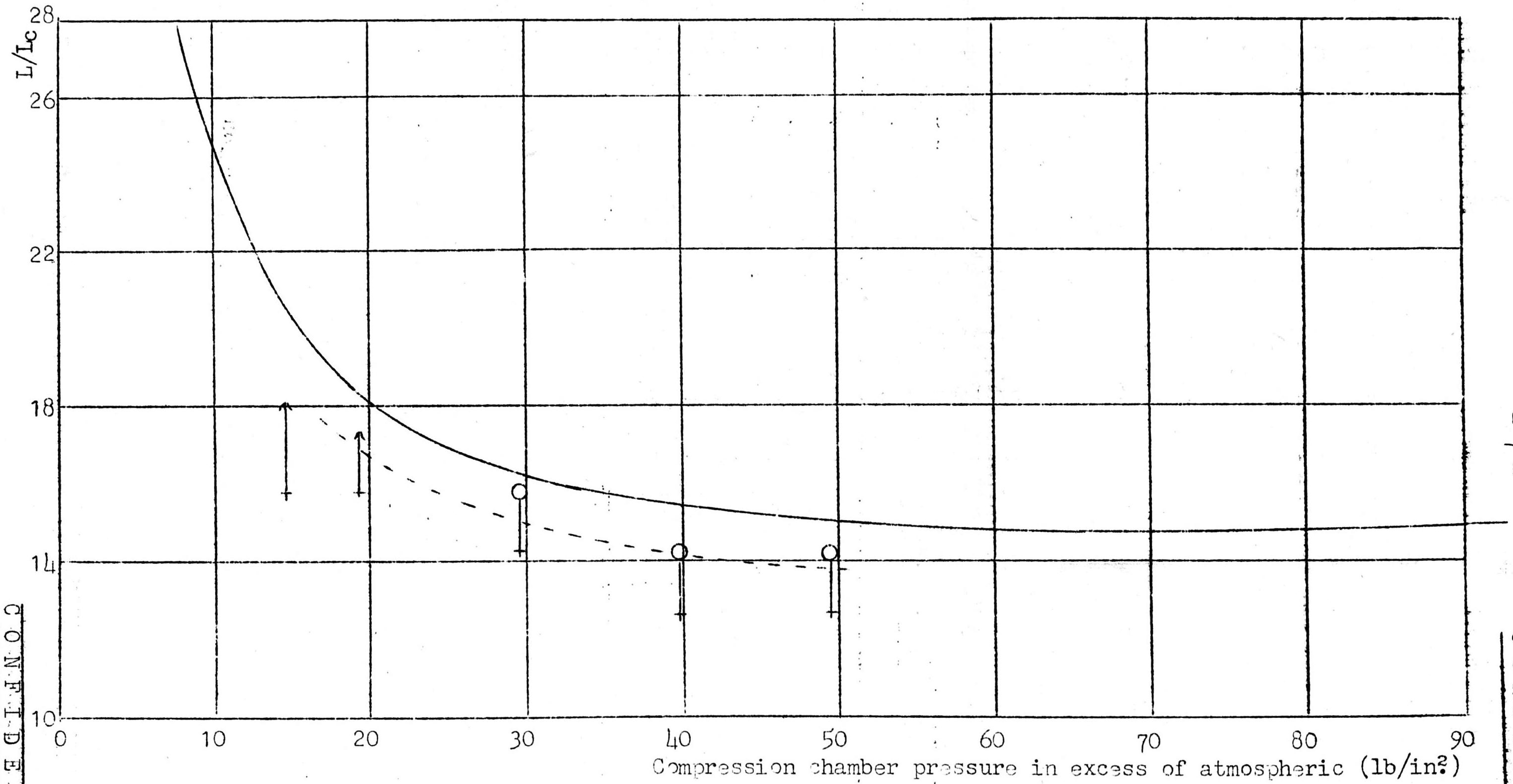

Fig. 3. Ratio of length of expansion chamber to compression chamber in order to produce a peaked shock wave.

——, calculated from known velocities of waves

– – –, calculated curve allowing for finite width of pressure gauge

o, points definitely giving peaked records

+, points that may be at catchup

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length of the flat top of the shock wave. It is obvious that when the length in space of the flat part of the pressure-time curve is equal to the width of the gauge the record will look essentially the same as it will at the true point of catchup. The vibrations of the gauge also interfere somewhat with the accuracy of determination of the point of catchup, although a line through the mean of the oscillations gives a reasonably good fit to the true shape of the curve.

An inspection of the records indicates that within the resolving power of the gauges, the catchup points are as given in Table III.

Table III. Catchup points.

Shot No.	Catchup points when L/L_c =				P_{cs} (lb/in².)	γ
	11.0	12.65	14.25	15.86		
1	no	no	no	no	8.9	1.27
2	no	no	no	?	14.8	1.41
3	no	no	no	?	19.1	1.50
4	no	no	?	yes	29.5	1.70
5	no	?	yes	---	39.8	1.87
6	no	?	yes	---	49.4	2.00

The points of catchup marked "yes" in the table are indicated as circles in Fig. 3. The questionable point at that same chamber pressure is marked by a cross with a line drawn from it to the circle to indicate the region of most uncertainty. The solid line is calculated from the known velocities of the various waves involved, while the dashed line is derived from a calculation (at two pressures) of the distance at which the flat part of the wave has the approximate width of the gauge. This line seems to fall quite well within the region that is marked as uncertain. One would infer from this that as the size of the gauge was reduced, the length of expansion tube necessary to produce a peaked wave would be at least closer to the computed curve.

Division 2, NDRC
Monthly Report AES-7 (OSRD-4754)
February 25, 1945

ADVANCE RELEASE: This information is tentative and subject to revision.

Projects OD-03, NO-224

Underwater Explosives Research Laboratory
P. C. Cross, Supervisor

THE AIR-BLAST PERFORMANCE OF SOME HIGH EXPLOSIVES

by W. D. Kennedy[1]

Abstract

Available data from many sources on measurements of blast peak pressure and positive impulse of seven high explosives have been compiled, and from them, estimates of the over-all average blast performance relative to one another have been made. The conclusions from this survey are as follows.

1. The peak pressure and positive impulse in the blast from the seven explosives, relative to those from Composition B (the comparison being on an equal-volume basis) are:

Explosive	Relative Peak Pressure	Relative Positive Impulse
Torpex 2	1.11	1.14
HBX	1.06	1.09
Minol 2	1.03	1.07
Tritonal	1.01	1.05
Composition B*	1.00	1.00
TNT	0.91	0.91
Amatol**	0.85	0.80

*Throughout this report, RDX/TNT, 60/40, is designated "Composition B."

**Applies to both Amatol 60/40 and 50/50.

2. Estimates of the relative areas of blast damage are: 1.30, Torpex 2; 1.19, HBX; 1.14, Minol 2; 1.10, Tritonal; 1.00, Composition B; 0.83, TNT; 0.64, Amatol.

3. The relative blast intensity was found to be independent of the following variables:

(a) Distance from the charge,
(b) Charge/weight ratio,
(c) Aluminum grist size (over a wide range of size).

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[1] The author is greatly indebted to Mrs. R. F. Arentzen for assistance in compiling the data on which this report is based.

4. The relative blast intensities of Minol and Tritonal were found to increase as the aluminum content was increased from 20% to 25% or 30%.

5. Overboostering bombs loaded with Minol 2 was found not to be necessary, although small bare charges may require it.

1. Introduction

The peak pressures and positive impulses in the air blast from bombs and charges of all sizes with several explosive fillings have been measured at four laboratories both in the United States and in Britain. The purpose of these tests was primarily to determine which of the acceptable proposed explosive compositions were to be preferred, using blast intensity as a criterion. It is the purpose of this report to summarize the major part of the recent work in this field, and to obtain a numerical factor for each explosive which represents its blast intensity relative to a corresponding quantity of one of the other explosives (chosen as a "standard") with which it has been compared. Two such intensity factors are obtained for each explosive: relative peak pressure and relative positive impulse. Since positive-impulse intensity is ordinarily used as a measure of expected blast damage radius, the merit of each of the explosives can be obtained in terms of the estimated relative areas of blast damage.

2. Relative peak pressures and positive impulses

The procedure used in this study was as follows.

(a) The average bomb loading density for each of the explosives considered was obtained. These "standard" loading densities are given in Table I, together with the usual compositions of the explosives.

(b) The peak pressures and positive impulses of TNT relative to those of Composition B were compiled from various sources, and were adjusted, where necessary, to take into account the differences between the actual loading densities and the "standard" densities of Table I. In order to do this, the dependence of peak pressure and positive impulse on charge weight was taken to be:

$$P_1/P_2 = (w_1/w_2)^{0.6} \text{ and } I_1/I_2 = (w_1/w_2)^{0.67},$$

Table I. Average densities and compositions of explosives.

Explosive	Density (gm/cm³)	Ammonium Nitrate	Composition[a] (percentage by weight)				
			RDX	TNT	Al	Wax	Calcium Chloride
Torpex 2[b]	1.71	---	42	40	18	0.7[c]	---
HBX	1.65	---	40	38	17	5[d]	0.5[c]
Minol 2	1.64	40	---	40	20	---	---
Tritonal, 80/20	1.65	---	---	80	20	---	---
Composition B	1.60	---	60	40	---	1.0[c]	---
TNT	1.55	---	---	100	---	---	---
Amatol, 60/40	1.56	60	---	40	---	---	---
Amatol, 50/50	1.55	50	---	50	---	---	---

a/ Under actual loading conditions, compositions vary by a few percent from the average values given here.

b/ Recently, it has become the practice to add 0.5% calcium chloride to this composition, and to refer to the resulting mixture as Torpex 3. It is thought that no appreciable effect on the blast would be noted.

c/ Not taken into account in percentages of other ingredients.

d/ D-2 desensitizing wax.

where P_1 is the pressure determined at a fixed distance from w_1 lb of explosive, and I_1 is the corresponding impulse, and so forth. These expressions are based on average experimentally determined exponents $n = 1.8$ and $m = 1.0$ in

$$P = A\left(\frac{w^{1/3}}{r}\right)^{n} \qquad (1)$$

and

$$\frac{I}{w^{1/3}} = B\left(\frac{w^{1/3}}{r}\right)^{m} \qquad (2)$$

where $\underline{P}$ is the peak pressure; $\underline{I}$, the positive impulse; $\underline{w}$, the weight of charge; $\underline{r}$, the distance from gauge to charge, and $\underline{A}$, $\underline{B}$, $\underline{m}$, and $\underline{n}$ are empirical constants. Since the corrections to "standard" densities were small (of the order of a few percent), errors in $\underline{n}$ or $\underline{m}$ have little effect on the corrections.

(c) The average peak pressure and positive impulse of TNT relative to those of Composition B were found to be 0.91 in each case. Thus, wherever only TNT and not Composition B was used in a series of air-blast measurements, the value 0.91 was used for the relative pressure and impulse of TNT relative to Composition B in the compilation.

(d) The peak pressures and positive impulses, relative to those of Composition B, for Torpex 2; HBX; Minol 2; Tritonal, 80/20; TNT, Amatol, 60/40 and 50/50, were adjusted to values consistent with the "standard" densities as described in (b). These data, together with references to their sources, are given in Table II.

(e) A table of all possible comparisons involving any two explosives in the set was then obtained, (for example, Torpex 2 to Minol 2, Torpex 2 to Tritonal, and so forth), and the standard deviations of the means were determined assuming the errors in the data to be normally distributed. These standard deviations of the mean ranged from a fraction of a percent to about 2% at most.

(f) Small arbitrary adjustments (of the order of 1%) to a few of the mean relative peak pressures and positive impulses were then applied to make the final table internally consistent. The final estimates are tabulated in Table III. It is estimated that the relative pressures and impulses in Table III are probably accurate to better than 2 or 3%.

Estimates of the relative areas of blast damage for the various explosives were obtained by squaring the relative impulses of Table III. These estimated relative areas of blast damage are tabulated in Table IV, and are represented graphically relative to Composition B in Fig. 1.

3. The variation of relative pressures and impulses with distance

In any given series of trials, the pressure (or impulse) from the bomb may have been found to decay with distance at different rates for different explosives; that is, the relative peak pressures (or positive impulses) were not found to be independent of distance in a limited number of experiments. However, examination of the results from a number of series of trials performed by various investigators leads to the conclusion that these apparent differences in rates of decay are not significant, and that, over a wide

Table II. Peak pressure and positive impulse ratios to Composition B, corrected to "standard" loading densities.

Note: Where Comp. B was not used, TNT was assigned the value 0.91 for both pressure and impulse relative to Comp. B.

Source[a]	Size	$P_x/P_{Comp.B}$						$I_x/I_{Comp.B}$					
		Torpex	HBX	Minol	Tritonal	TNT	Amatol	Torpex	HBX	Minol	Tritonal	TNT	Amatol
(a) Bare (cardboard-cased) charges													
(1)	60-lb	—	—	—	—	—	—	1.11	—	1.04	—	0.94	0.84[b]
(2)	45-lb	1.10	1.04	1.01	1.03	(0.91)	—	1.16	1.09	1.02	1.02	0.91	—
(3)	12.4-lb	1.13	—	1.04	—	—	—	1.12	—	0.97	—	—	—
	1.4-lb	1.11	—	—	—	0.92	—	1.15	—	—	—	0.90	—
(4)	1.7-lb	1.12	—	—	—	(0.91)	—	1.13	—	—	—	(0.91)	—
(5)	1.7-lb	—	—	—	0.98	(0.91)	—	—	—	—	1.02	(0.91)	—
(b) High-capacity and light-cased bombs													
(6)	10,000-lb	—	—	—	—	0.90	0.84[b]	—	—	—	—	0.96	0.81[b]
(7)	8,000-lb	—	—	—	—	—	—	1.11	—	1.09	—	—	—
(8)	4,000-lb	1.26	—	1.00	—	0.91	0.84	1.10	—	1.08	—	0.90	0.75
(9)	4,000-lb	—	—	—	—	—	—	1.08	—	1.08	—	—	—
(10)	4,000-lb	—	—	1.06	1.08	—	—	—	—	1.03	1.01	—	—
(11)	4,000-lb	1.12	—	1.04	—	(0.91)	—	1.11	—	1.04	—	(0.91)	—
(12)	4,000-lb	—	—	—	1.05	0.94	—	—	—	—	1.09	0.93	—
(13)	4,000-lb	—	—	—	—	—	—	—	—	1.07	—	—	—
		—	—	—	—	—	—	—	—	1.05	—	—	—
(14)	4,000-lb	—	—	—	—	—	—	—	—	1.06	—	—	0.75
(15)	4,000-lb	—	—	—	—	—	—	—	—	—	—	—	0.78[b]
(16)	4,000-lb	—	—	—	—	—	—	—	—	—	—	—	0.71
(17)	4,000-lb	—	—	—	—	—	—	—	—	—	—	—	0.72
(18)	4,000-lb	—	—	—	—	—	—	—	—	—	—	—	0.88
(19)	Various	—	—	—	—	—	0.85	—	—	—	—	—	0.79
(20)	350-lb DB	1.11	—	—	—	(0.91)	--	1.10	—	—	—	(0.91)	—
(c) Medium-capacity and general-purpose bombs													
(21)	4,000-lb	—	—	—	—	—	—	—	—	—	—	—	0.80
(22)	2,000-lb	1.11	—	1.04	—	0.93	0.92[b]	1.16	—	1.09	—	0.90	0.78[b]
(12)	2,000-lb	1.05	—	1.04	0.97	0.86	—	1.10	—	1.06	1.03	0.86	—
(23)	1,000-lb	—	—	—	—	—	—	—	—	—	—	(0.91)	0.85[b]
(9)	500-lb	—	—	—	—	—	—	1.18	—	1.18	—	—	—
(24)	500-lb	1.04	—	1.01	0.97	(0.91)	0.84	1.07	—	0.99	0.97	(0.91)	0.81
(25)	500-lb	1.14	—	1.07	1.03	0.93	—	1.15	—	1.13	1.11	0.94	—
(20)	500-lb	1.05	—	—	—	(0.91)	—	1.12	—	—	—	(0.91)	—
(26)	500-lb	1.14	1.08	—	0.98	—	—	1.14	1.10	—	1.02	—	—
(27)	500-lb	1.14	1.10	—	1.02	—	—	1.17	1.13	—	1.07	—	—
(28)	500-lb	—	—	—	—	—	—	—	—	—	1.14	0.91	—
(29)	500-lb	—	—	—	—	—	—	—	—	—	—	—	0.82
		—	—	—	—	—	—	—	—	—	—	—	0.81[b]
(30)	500-lb	—	—	—	—	—	—	—	—	—	—	—	0.82
(d) Low-capacity munitions													
(31)	60-lb rocket	—	—	—	—	—	—	1.25	1.25	1.22	—	(0.91)	—

[a] See listing at end of paper.

[b] Amatol, 50/50; values in this column not marked are Amatol, 60/40.

Table III. Relative peak pressures and positive impulses (equal volumes).

Each entry represents the peak pressure (or positive impulse) from the explosive at the left of the corresponding row divided by the peak pressure (or positive impulse) from the explosive at the top of the corresponding column. The values are probably accurate to better than 2 or 3%.

Explosive	Torpex 2	HBX	Minol 2	Tritonal	Composition B	TNT	Amatol[a]
Relative Peak Pressure							
Torpex 2	1.00	1.05	1.08	1.10	1.11	1.22	1.31
HBX	0.95	1.00	1.02	1.05	1.06	1.16	1.25
Minol 2	0.93	0.98	1.00	1.02	1.03	1.13	1.22
Tritonal	0.91	0.95	0.98	1.00	1.01	1.11	1.19
Comp. B	0.90	0.94	0.97	0.99	1.00	1.10	1.18
TNT	0.82	0.86	0.88	0.90	0.91	1.00	1.08
Amatol[a]	0.76	0.80	0.82	0.84	0.85	0.93	1.00
Relative Positive Impulse							
Torpex 2	1.00	1.04	1.07	1.09	1.14	1.25	1.42
HBX	0.96	1.00	1.03	1.04	1.09	1.20	1.36
Minol 2	0.94	0.97	1.00	1.02	1.07	1.18	1.34
Tritonal	0.92	0.96	0.98	1.00	1.05	1.16	1.32
Comp. B	0.88	0.92	0.94	0.95	1.00	1.10	1.25
TNT	0.80	0.83	0.85	0.86	0.91	1.00	1.14
Amatol[a]	0.70	0.74	0.75	0.76	0.80	0.88	1.00

[a] Amatol applies to both Amatol, 60/40 and 50/50.

Table IV. Estimated relative areas of blast damage using the impulse criterion (equal volumes of explosives).

Each entry represents the estimated damage area from the explosive at the left of the corresponding row divided by the estimated damage area from the explosive at the top of the corresponding column.

Explosive	Torpex 2	HBX	Minol 2	Tritonal	Composition B	TNT	Amatol[a]
Torpex 2	1.00	1.08	1.14	1.19	1.30	1.49	2.02
HBX	0.93	1.00	1.06	1.08	1.19	1.44	1.87
Minol 2	0.88	0.94	1.00	1.04	1.14	1.39	1.80
Tritonal	0.83	0.93	0.96	1.00	1.10	1.34	1.74
Comp. B	0.81	0.84	0.88	0.91	1.00	1.21	1.56
TNT	0.67	0.69	0.72	0.75	0.83	1.00	1.30
Amatol[a]	0.50	0.54	0.56	0.57	0.64	0.77	1.00

[a] Amatol applies to both Amatol, 60/40 and 50/50.

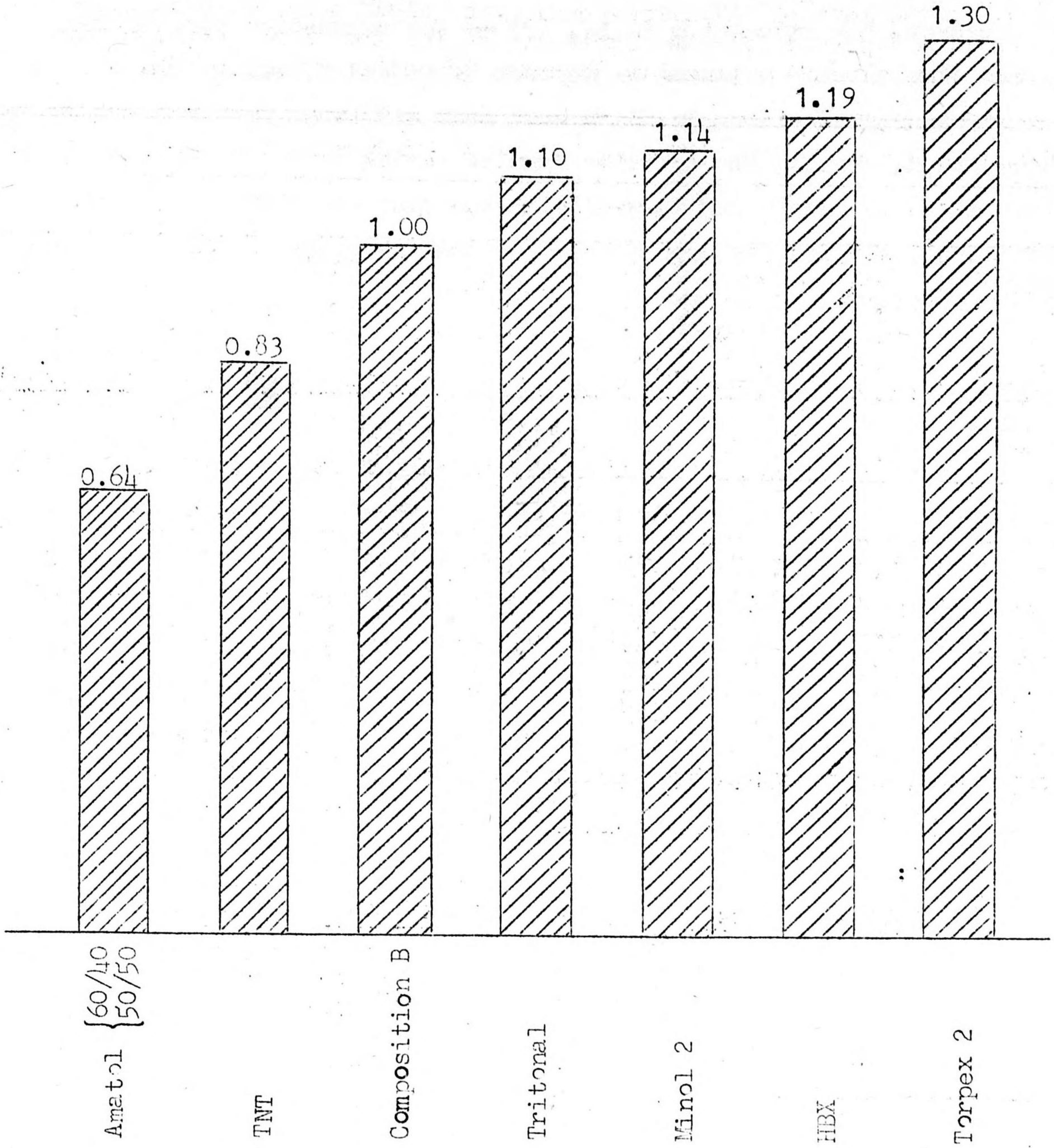

Fig. 1. Relative areas of blast damage from some high explosives (equal volumes). Heights of bars are proportional to estimated damage areas of any given category.

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range of distance, the relative pressures and impulses are essentially independent of distance.

Moreover, the exponent m in Eq. (2) -- the expression for the decay of positive impulse with distance -- appears to be unity, within the scatter of the various determinations in which both bomb and gauge were relatively close to the ground. Hence, the positive impulse varies as the two-thirds power of the weight of charge and inversely as the distance from the charge. This observation justifies the procedure of estimating areas of damage by squaring relative impulses.

4. Dependence of relative peak pressure and positive impulse on charge/weight ratio

It has been suggested that the performance of some explosives (notably those containing aluminum) is better relative to that of Composition B in MC or GP bombs than in HC or LC bombs. To test this hypothesis, the results for each type of bomb, including bare or card-cased charges, were averaged, and the standard deviations of the means were estimated, assuming a normal distribution of error within each type of charge. These averages, together with their standard deviations, and, for comparison, the corresponding grand average results from Table II, are tabulated in Table V.

In Table V, the following values appear to be significantly different from the mean:

Relative Pressure	Relative Impulse
Tritonal (Light cased)	Torpex 2 (Light cased)
	Minol 2 ("Bare")
	Amatol (Light cased)

Only two experimental data are included in the mean for the relative peak pressure of light-cased Tritonal, and in this case, the value is higher than the mean for all bombs. Moreover, the results from bare charges are in good agreement with those from medium-cased bombs.

In the case of the relative impulse of light-cased Torpex 2 which appears to be lower than that for both bare charges and low-capacity munitions, the same remark applies: the data are not consistent, but do not indicate necessarily a poorer performance in lightly-cased charges.

Bare charges of Minol 2 appear to give significantly lower blast impulses relative to Composition B than do either high-capacity or low-capacity

Table V. Relative peak pressures and positive impulses: dependence on charge/weight ratio.

Type Charge	Torpex 2	HBX	Minol 2	Tritonal	TNT	Amatol[a]
			$P_x/P_{Comp.B}$			
"Bare" or card-cased	1.12 ±.01	1.04	1.02 ±.01	1.00 ±.01	(0.91)	—
Light-cased bombs	1.12 ±.03	—	1.03 ±.03	1.06 ±.03	0.92 ±.03	0.84 ±.03
Medium-cased bombs	1.10 ±.01	1.09 ±.02	1.04 ±.01	1.00 ±.01	0.91 ±.02	0.88 ±.02
Over-all average	1.11	1.06	1.03	1.01	0.91	0.85
			$I_x/I_{Comp.B}$			
"Bare" or card-cased	1.13 ±.01	1.09	1.01 ±.01	1.02 ±.02	0.92 ±.01	0.84
Light-cased bombs	1.10 ±.01	—	1.06 ±.01	1.05 ±.02	0.93 ±.01	0.77 ±.01
Medium-cased bombs	1.14 ±.02	1.12 ±.03	1.09 ±.02	1.06 ±.02	0.90 ±.02	0.81 ±.02
Over-all average	1.14	1.09	1.07	1.05	0.91	0.80

[a] Amatol, 60/40 and 50/50, have been treated as one.

munitions. In view of the marked boostering effect with Minol bare charges (see Sec. 6), it seems probable that the discrepancy here is due to improper detonation of small bare charges.

Finally, the blast impulse performance of Amatol in light-cased bombs appears to be inferior to that in medium-cased bombs.

It can be concluded from the foregoing discussion that if the performances of some explosives differ, depending on the case-weight of the bomb, it is not borne out that aluminized explosives in general are relatively poorer in high-capacity bombs, and moreover that in cases where this appears to occur, the data are not consistent. Therefore, the relative peak pressures and positive impulses are considered to be independent of charge/weight ratio.

5. The effect of varying the aluminum content on the performance of explosives

(a) Minol containing various percentages of aluminum. — Two series of trials have been carried out in Britain in order to study the effect of varying the aluminum content of Minol, one series being with 4,000-lb HC bombs (Reference 15), the other with 500-lb MC bombs (Reference 32). These results are recapitulated in Table VI. Mean values from Armament Research Department and Road Research Laboratory results are quoted from Reference 15, and, for comparison, they are referred to Minol 2 rather than to Composition B.

Table VI. Relative pressures and impulses as a function of the aluminum content of Minol, relative to Minol 2.

Explosive	Aluminum (percent)	4,000-lb HC			500-lb MC	
		Density	Relative Peak Pressure	Relative Positive Impulse	Density	Relative Positive Impulse
Comp. B.	0	1.58	92.7	94.6	—	—
Minols	0 (Amatol, 50/50)	1.56	79.4	73.4	1.55	73.2
	4	—	—	—	1.57	79.6
	5	1.60	88.1	80.4	—	—
	8	—	—	—	1.61	?
	10	1.61	97.3	88.7	—	—
	12	—	—	—	1.63	?
	15	1.65	98.7	97.8	—	—
	16	—	—	—	1.65	94.2
	20 (Minol 2)	1.67	100.0	100.0	1.69	100.0
	24	1.67	100.5	105.1	1.72	102
	28	1.69	101.0	105.2	1.70	104

A significant improvement in both peak pressure and positive impulse is obtained by increasing the aluminum content of Minol from 20% to 28%. The data are in rough accord on this point. Note that there is no appreciable difference in the performance of the various Minols relative to Amatol, 50/50, in the two types of bomb. (See Sec. 4.)

(b) Tritonal containing various percentages of aluminum. — Three series of trials have been carried out in order to test the effect of varying the percentage of aluminum in Tritonal: one series was performed in Britain in 500-lb MC bombs (Reference 28), one at the Aberdeen Proving Ground in

500-lb GP bombs (Reference 25), and one at the Underwater Explosives Research Laboratory in small (1.7-lb) bare charges (Reference 5). The relative positive impulses are summarized in Table VII.

Table VII. Positive impulses relative to Composition B as a function of the aluminum content of Tritonal.

Composition	500-lb MC Bombs		500-lb GP Bombs		1.7-lb Bare Charges	
	Density	Relative Impulse	Density	Relative Impulse	Density	Relative Impulse
Composition B	—	(1.00)	—	(1.00)	—	—
TNT	1.53	0.90	1.56	0.92	(1.55)	(0.91)
TNT/Al,90/10	1.61	1.058	1.61	1.04	—	—
TNT/Al,85/15	1.63	1.082	—	—	1.65	1.02
TNT/Al,80/20	1.65	1.134	1.74	1.12	1.66	1.02
TNT/Al,75/25	1.69	1.173	—	—	1.69	1.05
TNT/Al,70/30	1.68	1.230	—	1.08	1.75	1.05
TNT/Al,65/35	1.74	1.193	—	—	—	—
TNT/Al,60/40	1.77	1.151	—	—	—	—

The data of Table VII indicate that an improvement in blast impulse is obtained as the aluminum content is increased up to 25% or 30%. The amount of improvement obtained at the optimum concentration of aluminum, however, differs considerably among the three sets of experiments. In the British experiments, it is found that the positive impulse from Tritonal, 70/30, is 23% better than that of Composition B. This implies a performance for Tritonal, 70/30, better by 8% than that given for Torpex 2 in Table III. Moreover, inspection of the original data in Reference 28 shows the measurements to be quite precise and the impulses given by the two standards of comparison, Composition B and TNT, to be in accord with other results.

It might be inferred from the foregoing that mixtures of TNT and aluminum are capable of considerably better performance than that ordinarily observed, if some as yet unknown variables were more carefully controlled. Supporting this hypothesis is the known tendency of TNT/Aluminum mixes to segregate.

6. The effect of overboostering Minol 2

It has been observed that the relative blast impulse from Minol 2 is greater in bombs than it is in bare charges (see Sec. 4). In order to discover whether or not this was due to underboostering, two series of bare-charge measurements (References 2 and 3) were performed using booster "caps" of Composition B on the Minol charge, the cap amounting to about 13% of the total charge weight. Other experiments pertinent to this point are those of Aberdeen Proving Ground with special overboostered 500-lb GP bombs (Reference 24), and with 4,000-lb LC bombs filled with Minol with various systems of boostering (Reference 11), and British tests involving 4,000-lb HC bombs with short exploders and a Composition B booster "cap" amounting to about 13% of the charge weight (Reference 14). The data from these tests are tabulated in Table VIII as pressures and impulses relative to Composition B and TNT. Numbers in parentheses are estimated on the basis of Table III.

The only appreciable effect of overboostering noticed is that of Reference 3 using 12.4-lb bare charges, and, to a lesser extent, of Reference 2 using 45-lb bare charges. A part, at least, of this boostering effect might conceivably have been due to special orientation effects involving distortion of the pressure fields around the charges. In this series, the gauges were located off the side of the charges. The fact that the boostering effect had largely vanished at the 45-lb scale, and that the relative pressures and impulses were found to be very nearly those obtained with bombs may indicate that the underboostering phenomenon is limited to charges of somewhat less than 45-lb weight.

The conclusion is certainly that it is not necessary to provide special boostering for Minol in bombs, and that there is no advantage in doing so.

7. The effect of aluminum grist size on blast impulse

Many tests involving Torpex 2 and Minol 2 have been made, using aluminum of various grist sizes, in both small bare charges and bombs. These tests are in close agreement in showing that no detectable differences in blast impulse are observed over the range of grist sizes 12 mesh-to-dust to 200 mesh-to-dust. It should be observed, however, that a considerable fraction of the aluminum passed a 200-mesh screen, and indeed, a 325-mesh screen, even in the coarsest grist used. Tests with 45-lb bare charges of Torpex 2 using standard (100 mesh-to-dust) and a "coarse cut" (through 50 mesh on 150 mesh) indicated no significant difference between the two fillings.

Table VIII. Effect of overboostering Minol 2.

Numbers in parentheses are estimated on the basis of Table III.

Source	Booster	Nose Surround	Type Charge	P_{Minol}/P_x		I_{Minol}/I_x	
				Comp. B	TNT	Comp. B	TNT
(2)	Cap, 13% Comp. B		45-lb, bare	(1.03)	1.13	(1.06)	1.16
	Standard, 320 gm		45-lb, bare	(1.01)	1.11	(1.02)	1.12
(3)	Cap, 13% Comp. B		12.4-lb, bare	1.13	(1.24)	1.13	(1.24)
	Standard, 160 gm		12.4-lb, bare	1.04	(1.14)	0.97	(1.07)
(11)	Auxiliary:		4000-lb LC bomb				
	Standard	Standard		(1.05)	1.15	(1.04)	1.14
	None	Standard		(1.03)	1.13	(1.04)	1.14
	2-in. axial	Standard		(1.05)	1.15	(1.05)	1.15
	Standard	100-lb TNT		(1.03)	1.13	(1.06)	1.16
	None	100-lb TNT		(1.03)	1.13	(1.06)	1.16
(14)	Short exploder plus cap, 13% Comp. B		4000-lb HC bomb			1.06	(1.16)
(25)	Full-length auxiliary booster	60-lb Comp.B	500-lb GP bomb	(1.01)	1.11	(1.01)	1.11

It has been concluded that the aluminum grist size has no effect on the blast performance of these explosives over a wide range of sizes.

8. Other methods of obtaining improved blast performance

Although the purpose of this report is to compare the blast performance of several explosives with a view to assisting in the choice of the best explosive for bombs, it is not out of place to discuss here, briefly, a few other means of improving blast performance.

(a) Large bombs. — Against certain less-resistant targets, where relatively low pressures but large impulses (that is, long durations) are required, the use of large bombs such as 4,000-lb LC and larger should produce a blast damage area per unit weight of bomb load considerably in excess of that obtained with smaller bombs. (See Reference 33.)

(b) Light cases. — For blast demolition purposes, where bombs are fuzed instantaneous, and where penetration of the target is neither necessary nor desirable, the case thickness can be reduced to the minimum necessary for ease of handling, with considerable gain in area of damage per unit weight of explosive, and with still greater gain per unit weight of bomb. The use of aluminum for bomb cases has been proposed and tested by the British (see Reference 13) and marked increases in blast impulse were obtained.

(c) Fuzing. — Where maximum blast damage is the goal, air-burst rather than impact-burst affords a method of increasing blast damage to some less resistant structures. Increases in the areas of demolition (as well as of less severe damage) of the order of 50% to 70% are expected by this means (see Reference 20).

LIST OF REFERENCES

Where subject matter is also reported elsewhere, it is so indicated under "Other reports" in each case.

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EFFECT OF BURIED CHARGES ON CONCRETE SURFACE SLABS

by D. G. Kretsinger and A. H. Taub

Abstract

Results of tests in which buried charges were detonated under concrete slabs indicate that the thickness $\underline{t}$ of the slab divided by the cube root of the charge weight $\underline{w}$ is a measure of the strength of the slab, as is the reinforcing; the strength increases with both of these quantities. At a given depth of the charge the stronger slabs suffer less damage. As the depth increases, the damage decreases. Tamping the charge increases the damage slightly.

Quantitative estimates are given for the limiting values of $t/w^{1/3}$ for which complete destruction of the slab is achieved over the crater area. It is argued that this type of damage will be achieved when the fuze selected is the one that will create the greatest crater area in unsurfaced soil. The presence of concrete slabs of the thicknesses used here does not appreciably affect the diameters of craters produced by the buried charges.

It is felt that these results may be scaled up and applied to the problems involved in selecting bombs and fuzes in the attack of concrete airport runways, road embankments with retaining walls, and concrete floors of heavy structures.

1. Introduction

The purpose of the tests reported herein was to determine the effect of different variables on damage to concrete slabs in contact with the ground that is produced by buried charges. The charge variables studied were weight, depth of burial, and method of burial. The slab variables were thickness, reinforcing, and restraint. Another purpose was to determine the influence of the presence of a concrete slab on the cratering of a charge in earth.

It is felt that these results may be scaled up and applied to the problems involved in selecting bombs and fuzes in the attack of concrete airport runways, road embankments with retaining walls, and concrete floors of heavy structures.

2. Experimental procedure

The slabs used were square in plan area, having $6\frac{1}{2}$-ft sides. Two thicknesses were used, 2 in. and 4 in. Some of the slabs had precast circular holes 5 in. in diameter to simulate the hole made by a bomb in perforating a concrete slab.

Tests were made with and without sand bags to restrain two edges of the slab. In the former case fourteen 75-lb bags were placed on each of two edges of the slab.

Three degrees of reinforcing were used. The 2-in. slabs had either no reinforcing or were reinforced with two mats of 2 × 2-in. No. 12 wire mesh, one in each face. This amounted to about 194 lb of reinforcing per cubic yard of concrete. The 4-in. slabs either had no reinforcing; or had two mats of the type described for the 2-in. slabs, giving a reinforcing of about 97 lb per cubic yard of concrete; or had two mats of $4 \times 4 \times \frac{1}{4}$ in. reinforcing, one in each face, giving a reinforcing of about 194 lb per cubic yard of concrete.

The charges were built up from $\frac{1}{2}$-lb Engineer blocks of TNT, which are rectangular parallelepipeds $1\text{-}3/4 \times 1\text{-}3/4 \times 3\frac{1}{4}$ in. The sizes used weighed $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, and 4 lb. The 1-lb charge was made by placing two of the blocks end to end to obtain a charge $1\text{-}3/4 \times 1\text{-}3/4 \times 6\frac{1}{2}$ in. The $1\frac{1}{2}$-lb charge was made by placing a 1-lb and a $\frac{1}{2}$-lb charge next to each other with their long axes parallel and the center of the $\frac{1}{2}$-lb charge opposite the center of the 1-lb one. The 2-lb charge was obtained by placing two 1-lb charges side by side, giving a charge $1\text{-}3/4 \times 3\frac{1}{2} \times 6\frac{1}{2}$ in. The 4-lb charge was obtained by placing two 2-lb ones side by side, giving a charge $3\frac{1}{2} \times 3\frac{1}{2} \times 6\frac{1}{2}$ in. The charges were detonated with Engineer caps; the larger charges were boostered with 22-gm tetryl cylinders.

The charges were buried with their long axis in one of two positions: parallel to or making an angle of 25° with the normal to the slab. In all cases the charge was approximately under the center of the slab. The perpendicular distance between the center of the charge and the bottom of the slab is referred to as the depth of the charge. When the charge axis was tilted with respect to the normal to the slab, the hole in

Fig. 1. A damage: Slab is completely destroyed and only a few isolated pieces of concrete remain.

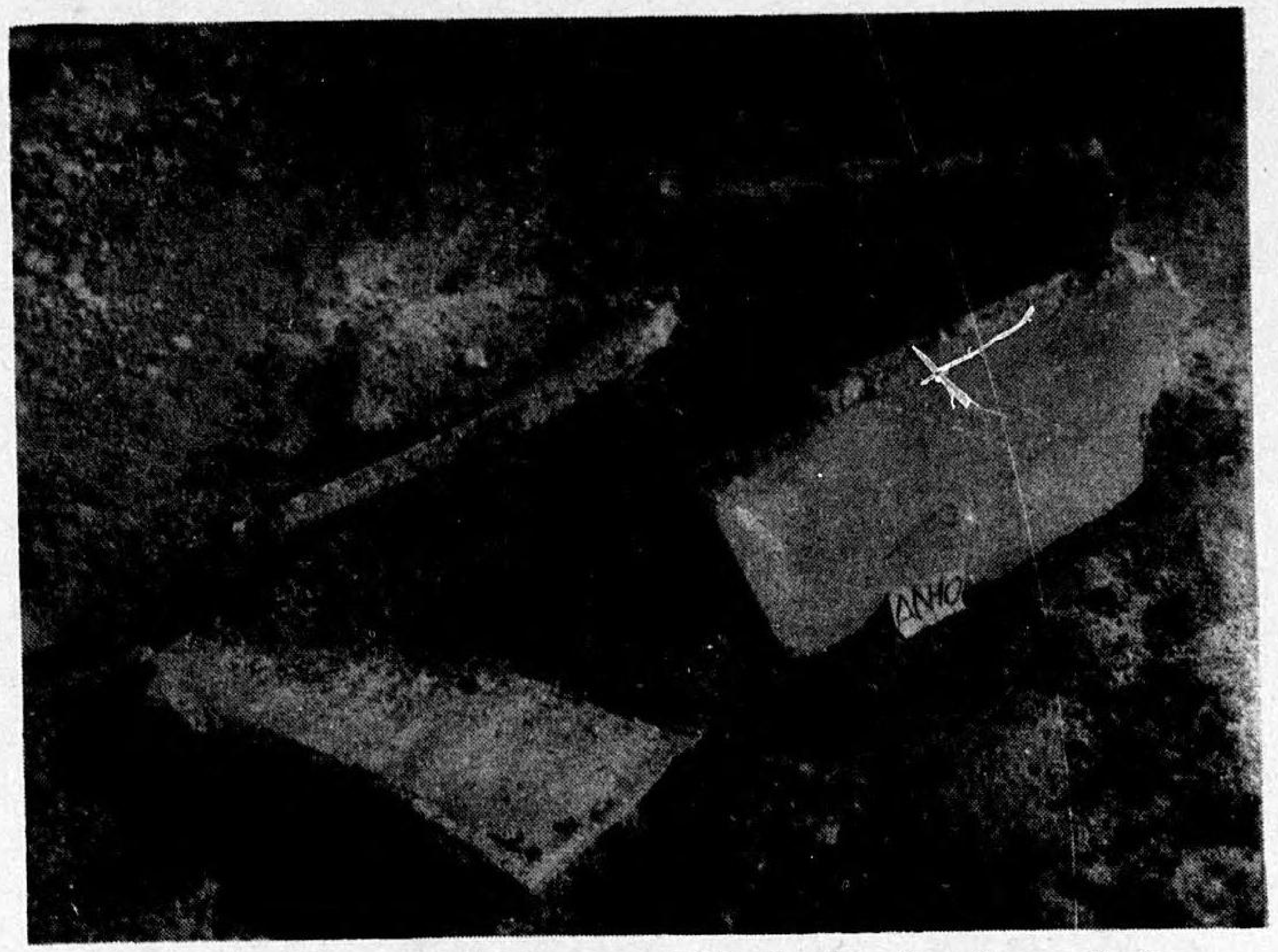

Fig. 2. B damage: Slab is broken into several large pieces, but they have not been thrown clear of the crater.

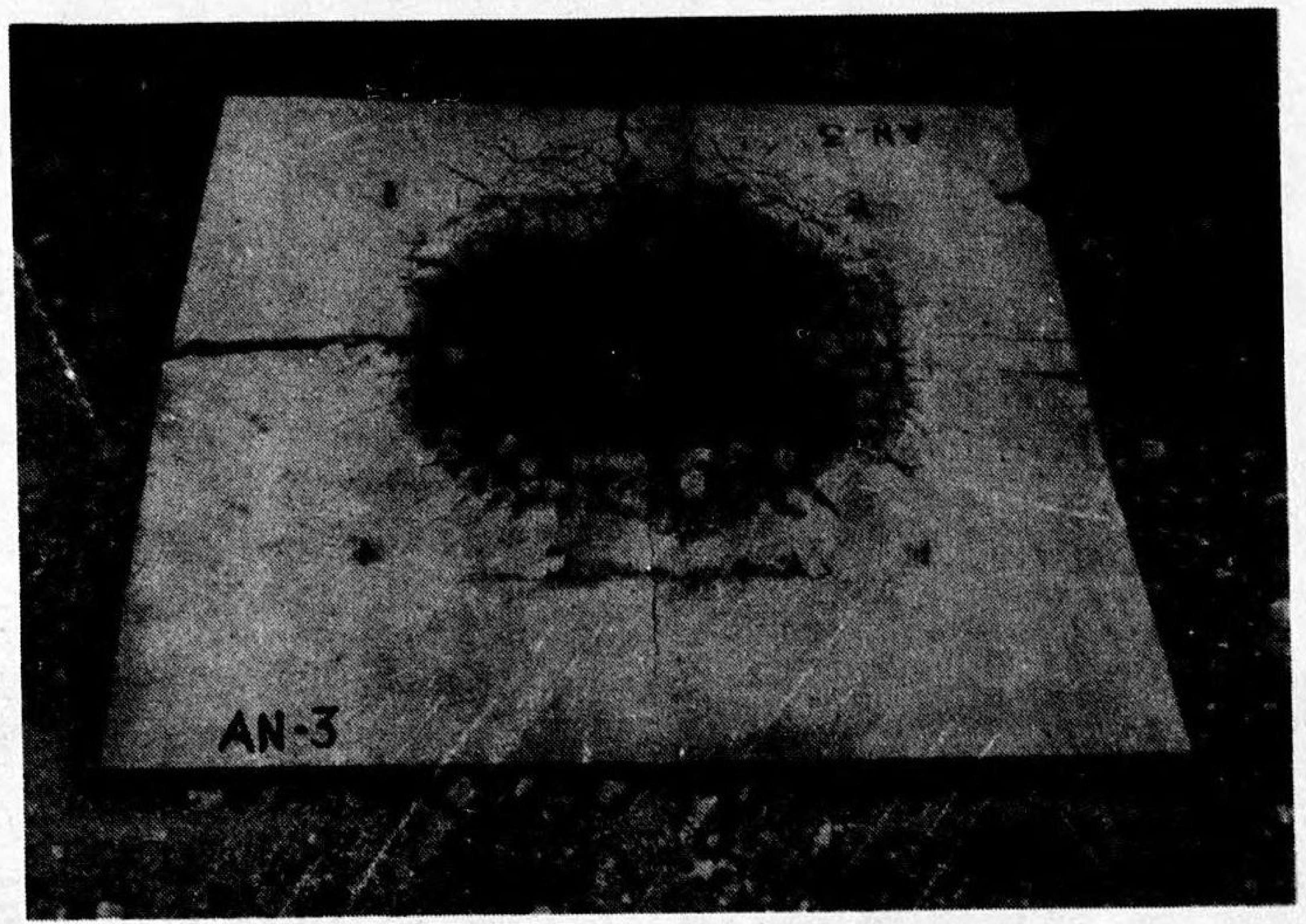

Fig. 3. C damage: Slab has a hole blown in it, with heavy cracks radiating to edges. Concrete pieces remain in place relatively intact.

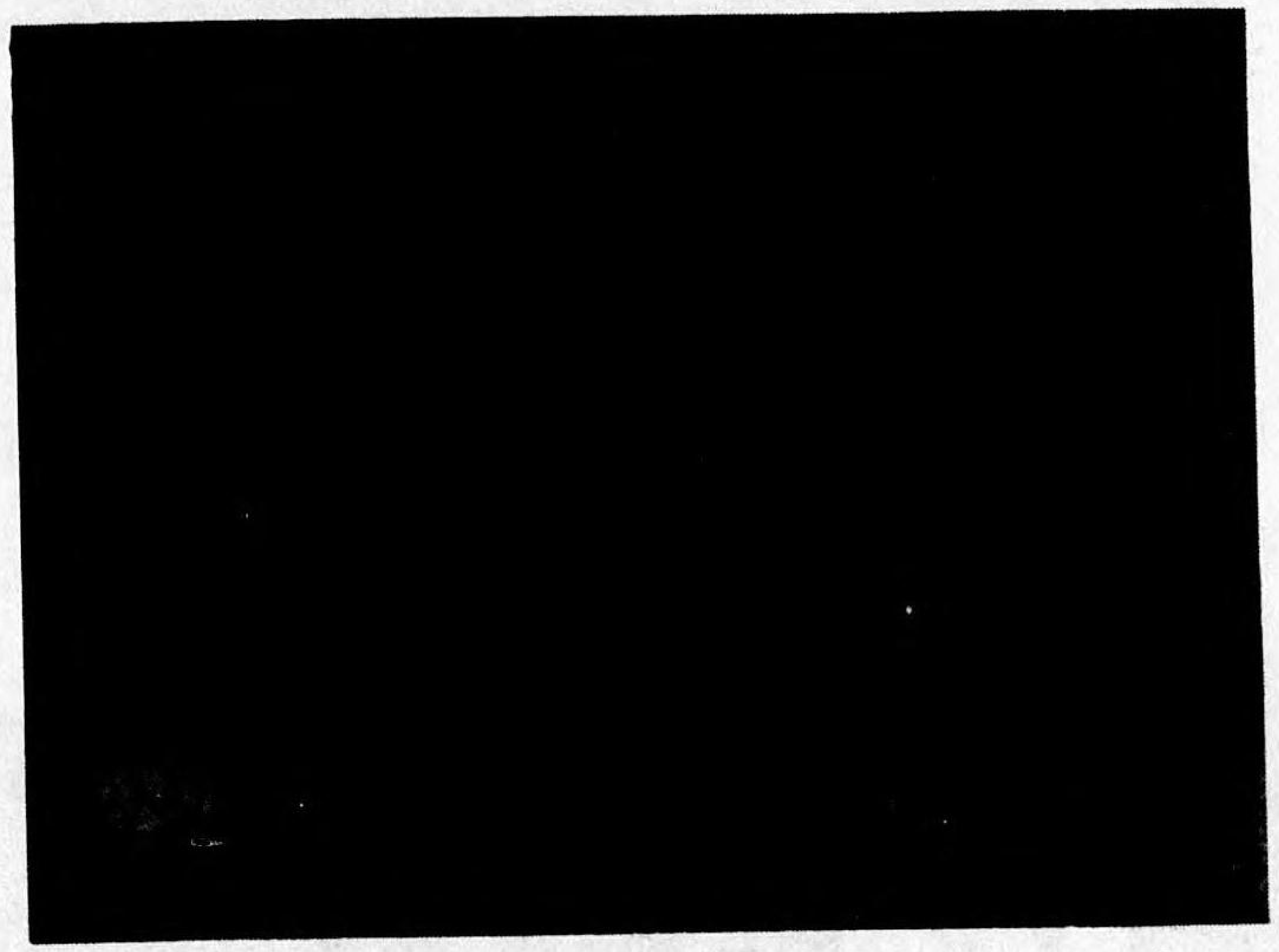

Fig. 4. D damage: Slab experiences heavy radial cracking, some of the cracks extending to edges of slab.

the ground into which the charge was inserted was so tilted. In some cases this hole was filled after the charge was inserted and the fill was compacted. In tests where this was done the charge is said to be a tamped charge.

The charge depths used were determined in terms of fractions of the depths necessary to produce a maximum crater in free earth. Previous experiments in the soil that was used (that in the vicinity of Princeton University Station -- undisturbed, dry, hard, Sassafras clay loam) had shown that this depth is achieved when the depth L (ft) divided by the cube root of the weight of charge w (lb) is 2.5, that is, $L/w^{1/3} = 2.5$. The depths that were used expressed in feet divided by 2.5 times the cube root of the weight of the charge in pounds were chosen to be 0, 1/3, 1/2, 2/3, or 1. The depths of the charges are referred to in the following by the value of this fraction. For example, if w (lb) is the charge weight and the depth is listed as 1/3, then the depth in feet is $(1/3)(2.5w^{1/3})$.

Before the slabs were put in place small amounts of sand were used to level minor inequalities in the ground and to provide a level bearing surface for the slab. The slab and charge were put in place, and the charge was detonated. The slab was then surveyed and the damage was listed as A, B, C, D, or intermediate. Thus B-A damage is intermediate between B and A and closer to B. The definition of these categories is as follows:

A: The slab is completely destroyed and only a few isolated pieces of concrete remain (see Fig. 1).

B: The slab is broken into several large pieces, but these have not been thrown clear of the crater (see Fig. 2).

C: The slab has a hole blown in it, with heavy cracks radiating to the edges. However, the concrete pieces remain in place and are relatively intact (see Fig. 3).

D: The slab experiences heavy radial cracking, some of the cracks extending to the edges of the slab (see Fig. 4).

The slab was then removed and the apparent crater underneath it was profiled. Only the diameters of the apparent craters are reported here.

3. Results

The results of the seventy-two tests performed are listed in Table I. In the first column of the table is listed the number of the test in order

Table I. Damage to concrete surface slabs produced by buried charges.

Slab No.	$\frac{L}{2.5w^{1/3}}$	$\frac{t}{w^{1/3}}$	Category of Damage	Presence or Absence of:					Slab Thickness (in.)	Charge Weight, $\underline{w}$ (lb)	$D/w^{1/3}$ (ft/lb$^{1/3}$)	Crater Diameter, $\underline{D}$ (ft)
				Reinforcing	Tamping	Restraint	Bomb Hole	Slant				
64	0	0.167	A	–	–	+	+	+	4	1.0	4.00	4.00
63	0	.210	A	–	–	+	+	+	4	0.5	4.63	3.67
52	0	.333	A	–	–	+	+	+	4	1.0	4.67	4.67
51	0	.420	A	–	–	+	+	+	4	0.5	5.04	4.00
											Avg. 4.59	
24	0	.210	A	+	–	+	–	–	4	4.0	3.57	5.67
32	0	.210	A	+	–	+	+	–	4	4.0	5.13	8.16
21	0	.333	C-B	+	–	+	–	–	4	1.0	3.50	3.50
29	0	.333	A	+	–	+	+	–	4	1.0	4.83	4.83
65	0	.333	C	x*	–	+	+	+	4	1.0	3.83	3.83
											Avg. 4.17	
4	0	.105	A	x	+	–	–	–	2	4.0	3.54	5.63
3	0	.132	C	x	+	–	–	–	2	2.0	3.97	5.00
2	0	.167	C	x	+	–	–	–	2	1.0	4.34	4.34
1	0	.210	C	x	+	–	–	–	2	0.5	3.15	2.50
											Avg. 3.75	
											Grand Avg. 4.17	
8	1/3	0.105	A	x	+	–	–	–	2	4.0	3.98	6.33
7	1/3	.132	A	x	+	–	–	–	2	2.0	4.90	6.17
6	1/3	.167	C	x	+	–	–	–	2	1.0	4.92	4.92
5	1/3	.210	C	x	+	–	–	–	2	0.5	4.04	3.17
											Avg. 4.46	
57	1/2	0.132	A	–	–	+	+	+	2	2.0	5.15	6.50
55	1/2	.167	A	–	–	+	+	+	2	1.0	5.17	5.17
60	1/2	.167	A	–	–	+	–	+	2	1.0	4.66	4.66
53	1/2	.210	A	–	–	+	+	+	2	0.5	3.99	3.17
59	1/2	.210	A	–	–	+	–	+	2	0.5	4.67	3.66
47	1/2	.264	A	–	–	+	+	+	4	2.0	5.13	6.46
43	1/2	.333	B	–	–	+	+	+	4	1.0	5.17	5.17
50	1/2	.333	A	–	–	+	–	+	4	1.0	--	--
41	1/2	.420	D-C	–	–	+	+	+	4	0.5	2.84	2.25
49	1/2	.420	A	–	–	+	–	+	4	0.5	--	--
											Avg. 4.60	
72	1/2	.210	B	+	–	+	+	+	4	4.0	3.98	6.33
27	1/2	.264	A	+	–	+	–	+	4	2.0	5.15	6.50
71	1/2	.264	D	x	–	+	+	+	4	2.0	4.33	5.46
66	1/2	.333	D	x	–	+	+	+	4	1.0	4.25	4.25
70	1/2	.333	C	x	–	+	–	+	4	1.0	5.13	5.13
											Avg. 4.57	
36	1/2	.264	A	+	+	–	+	+	4	2.0	4.90	6.17
35	1/2	.264	A	+	+	+	+	+	4	2.0	5.41	6.83
39	1/2	.264	A	+	+	+	+	–	4	2.0	5.16	6.50
37	1/2	.290	A	+	+	+	+	+	4	1.5	5.23	6.00
68	1/2	.333	C	+	+	+	+	+	4	1.0	4.67	4.67
											Avg. 5.12	
											Grand Avg. 4.81	

*x means heavy reinforcing was present.

Table I. [Concluded.]

Slab No.	$\frac{L}{2.5W^{1/3}}$	$\frac{t}{W^{1/3}}$	Category of Damage	Presence or Absence of:					Slab Thickness (in.)	Charge Weight, W (lb)	$D/W^{1/3}$ ($ft/lb^{1/3}$)	Crater Diameter, D (ft)
				Reinforcing	Tamping	Restraint	Bomb Hole	Slant				
58	2/3	0.132	A	–	–	+	+	+	2	2.0	4.23	5.33
56	2/3	.167	A	–	–	+	+	+	2	1.0	--	--
54	2/3	.210	A	–	–	+	+	+	2	0.5	5.45	4.33
48	2/3	.264	A	–	–	+	+	+	4	2.0	5.95	7.50
44	2/3	.333	B	–	–	+	+	+	4	1.0	4.84	4.84
42	2/3	.420	D-C	–	–	+	+	+	4	0.5	1.74	1.38
											Avg. 4.44	
20	2/3	.167	D	x	–	+	+	+	2	1.0	6.00	6.00
18	2/3	.210	D	x	–	+	+	+	2	0.5	6.40	5.08
23	2/3	.264	A	+	–	+	–	–	4	2.0	3.90	4.92
26	2/3	.264	A	+	–	+	–	+	4	2.0	4.23	5.33
31	2/3	.264	A	+	–	+	+	–	4	2.0	5.15	6.50
25	2/3	.333	A	+	–	+	–	+	4	1.0	3.76	3.76
30	2/3	.333	A	+	–	+	+	–	4	1.0	--	--
22	2/3	.333	C-B	+	–	+	–	–	4	1.0	5.66	5.66
67	2/3	.333	D	x	–	+	+	+	4	1.0	--	--
											Avg. 5.01	
12	2/3	.105	A	x	+	–	+	+	2	4.0	4.88	7.75
11	2/3	.132	A	x	+	–	+	+	2	2.0	5.42	6.83
10	2/3	.167	B	x	+	–	+	+	2	1.0	5.25	5.25
9	2/3	.210	D	x	+	–	+	+	2	0.5	6.73	5.34
											Avg. 5.57	
19	2/3	.167	C-B	x	+	+	+	+	2	1.0	6.50	6.50
17	2/3	.210	D	x	+	+	+	+	2	0.5	8.60	6.83
34	2/3	.264	A	+	+	+	+	+	4	2.0	5.30	6.67
38	2/3	.264	A	+	+	+	+	+	4	2.0	6.21	7.83
40	2/3	.290	B	+	+	+	+	–	4	1.5	5.26	6.04
33	2/3	.333	A	+	+	+	+	+	4	1.0	--	--
											Avg. 6.37	
											Grand Avg. 5.31	
16	1.0	0.105	D	x	+	–	+	+	2	4.0	6.20	9.88
15	1.0	.132	D	x	+	–	+	+	2	2.0	5.75	7.25
14	1.0	.167	D	x	+	–	+	+	2	1.0	6.83	6.83
13	1.0	.210	D	x	+	–	+	+	2	0.5	6.72	5.33
											Avg. 6.38	
28	1/2	0.264	A	+	–	–	–	+	4	2.0	5.02	6.50
69	1/2	.333	D	x	–	–	+	+	4	1.0	4.96	4.96
61	1/2	.167	A	–	–	–	+	–	2	1.0	6.13	6.13
45	1/2	.333	A	–	–	–	+	–	4	1.0	6.13	6.13
62	2/3	.167	A	–	+	–	+	+	2	1.0	6.00	6.00
46	2/3	.333	A	–	+	–	+	+	4	1.0	5.25	5.25

of its performance. The second gives the fractional depth of the charge as described in Sec. 2. The third gives the thickness t (ft) of the slab divided by the cube root of the weight w (lb) of the charge. The fourth gives the category of damage in accordance with the classification as just described. In the next five columns plus and minus signs are used to denote the presence or absence of the quantity given at the head of the various columns. In the reinforcing column the x sign is used in addition to denote the presence of very heavy reinforcing. For example, the entries in these columns in the row giving the result of test 65 are to be read as follows: The slab used here had heavy reinforcing; the charge was not tamped; restraining bags were on the slab; there was a precast hole in the slab; and the charge was buried with its long axis making an angle of 25° with the normal to the slab. The tenth column gives the slab thickness in inches; the eleventh the weight of the charge in pounds; the twelfth the apparent crater diameter in feet divided by the cube root of the weight of the charge in pounds; and the thirteenth the crater diameter in feet.

(a) Crater diameters. Table I gives the average value of $D/w^{1/3}$ for each group of tests in which the conditions of reinforcing, tamping, and restraint are the same for a given fractional depth of burial of the charge, as well as the average value of $D/w^{1/3}$ for all the tests in which only the fractional depth is fixed. The latter is called the grand average. The grand averages are within approximately 10 percent of the value of $D/w^{1/3}$ for free earth for the corresponding values of the fractional depth. The latter were obtained from the Weapon Data Sheet 3B1[1/] by reading the value of $D/w^{1/3}$ corresponding to a value of $L/w^{1/3}$ given by 2.1f, where f is the fractional depth. The grand averages at fractional depths 0 and 1 are slightly above the free-earth $D/w^{1/3}$ increased by 10 percent, and those for fractional depths 1/3 and 1/2 are slightly below the free-earth $D/w^{1/3}$ decreased by 10 percent. The average value of $D/w^{1/3}$ at fractional depth 2/3 is less than 10 percent smaller than the corresponding free-earth $D/w^{1/3}$.

There is no apparent systematic variation of the averages of $D/w^{1/3}$ for fixed fractional charge depth and fixed conditions of reinforcing,

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[1/] "Weapon Data - Fire, Impact, Explosion," Division 2, NDRC (Confidential).

tamping, and restraint about the grand average of $D/w^{1/3}$ for fixed fractional charge depth.

Moreover, within the range tested here there seems to be no systematic variation of $D/w^{1/3}$ for fixed charge depth with $t/w^{1/3}$.

The data in Table I are on the whole consistent with the conclusion that the presence of a concrete slab does not alter the crater diameter produced by a charge at a given depth below the surface of the ground by more than 15 percent from that obtained in free earth when the same charge is detonated at the same depth. Of course, the data in Table I apply only for $t/w^{1/3} \leq 0.420$, and it may be expected that for larger values of $t/w^{1/3}$ some influence of the slab will be felt. Such influence will be in the direction of producing camouflets for smaller depths of burial when slabs are present than when they are not. Some evidence for this was found in other tests, which will be reported separately.

(b) Scale laws. The data on crater diameters show that as far as the phenomena in earth are concerned, the usual scale laws hold within the test-to-test variations. This is to be expected if the thickness of the slab plays no important role, for these laws are known to hold in free earth.

The slab thickness has been used in organizing the data in the quantity $t/w^{1/3}$. This variable has been chosen because it is a "nondimensional" measure of the thickness and because data on breaching of underground walls indicate that it, together with the "nondimensional" distance between slab and charge (in this case $L/w^{1/3}$), is an important variable in determining the behavior of the slab.

In tests 72 and 59, 24 and 63, 24 and 1, the same values of $t/w^{1/3}$ and of fractional depth were used, although different thicknesses and charge weights were involved. The difference in damage to the slab is accounted for by the difference in reinforcing, as will be discussed later.

These tests are considered to be a verification of the scaling laws, which are expected to hold in this case because it is felt that at these small distances between charge and slab and for fixed conditions of restraint the forces of gravity are not important. When they are important, scaling in this manner does not take into account all factors.

(c) Damage to slabs. Inspection of Table I shows that the degree of damage can be influenced in a regular manner by the variables $t/w^{1/3}$, fractional depth, reinforcing, tamping, and restraint. The presence or absence of a bomb hole and the slant of the charge seem to produce random changes.

For any fixed fractional depth of charge the damage remains constant or decreases with $t/w^{1/3}$ for fixed conditions of reinforcing, tamping, and restraint. The value of $t/w^{1/3}$ at which this decrease starts, called the limiting $t/w^{1/3}$, is smaller for moderately reinforced slabs than for unreinforced ones and decreases still further for heavily reinforced slabs. Tamping the charge has a tendency to increase this value of $t/w^{1/3}$, as does increasing the restraint. Of these two factors the restraint plays the more important role.

As the fractional depth of charge increases, the value of the limiting $t/w^{1/3}$ remains unchanged or decreases; that is, for a fixed $t/w^{1/3}$ the damage will decrease as the fractional depth increases.

These results are all to be expected if one considers the quantities $t/w^{1/3}$ and the reinforcing as measures of the strength of the slab, and fractional depth and tamping as measures of the strength of the charge.

Table II gives the value of $t/w^{1/3}$ for which damage less than A damage may be expected for various fractional depths under different conditions of reinforcing, tamping, and restraint.

Table II. Limiting values of $t/w^{1/3}$ for A damage.

$L/2.5w^{1/3}$	Limiting Value of $t/w^{1/3}$	Presence or Absence of:		
		Reinforcing	Tamping	Restraint
0	>0.420	-	-	+
1/2	.333	-	-	+
2/3	.264	-	-	+
0	0.333	+	-	+
1/2	.264	+	-	+
2/3	.264-0.333	+	-	+
0	0.105	+	+	-
2/3	≤ .132	+	+	-
1	< .105	+	+	-
1/2	0.290	+	+	+
2/3	0.290	+	+	+
1/3	0.132	x*	+	-

*x means that heavy reinforcing was present.

4. Application to airport runways

Although the tests did not simulate the conditions of restraint obtaining in an airport runway, the results of tests conducted on a model airport runway are in general agreement with those given here and will be reported separately.

When an unsurfaced runway is attacked, bombs and fuzes are chosen to obtain a maximum crater area per pound of bomb consistent with bomb-loading characteristics of the planes used. This usually means small bombs (100-lb GP to 500-lb GP) fuzed for 0.01 to 0.025 sec delay. These bombs are expected to penetrate to a depth that will produce a maximum crater.

Most surfaced runways may be considered as being intermediate between an unsurfaced one and one having a 9-in. layer of unreinforced concrete. A bomb that is fuzed for maximum crater in free earth in attack on such a runway will only achieve a smaller depth in penetrating into the concrete and then the soil. If we assume that the fractional depth is 2/3, then the limiting value of $t/w^{1/3}$ is approximately $\frac{1}{4}$. Hence for charges greater than 27 lb, we will obtain A damage; that is, for the smallest bomb we could use, the 100-lb GP, we will obtain A damage. This is also true when the surface concrete is 12-in. thick.

It is unlikely that fuzing for a longer delay will markedly increase the penetration into the soil below the runway. Hence, we should expect that in almost all cases A damage will be produced in the bombing of surfaced runways.

Whether A damage is a desirable type of damage will, of course, depend upon the repair facilities available. One can conceive of instances where camouflets covered by relatively intact surfacing material would be harder to repair than A damage. However, this is probably an academic question since with present bombs and fuzes A damage will occur except where very deep penetrations are accidentally achieved.

The extent of the damage to the surface of the runway will be confined to a circular area whose radius is slightly larger than the crater radius. This radius in feet is approximately $2.0w^{1/3}$ to $2.5w^{1/3}$ for soil conditions normally found in airfields.