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MONTHLY REPORT NO. EWT-6 (OSRD NO. 5657)

G-2

EFFECTS OF WEAPONS ON TARGETS

Volume 6. September 5, 1945

A Compilation of Informal Reports Submitted in Advance of Formal Reports

Issued by Division 2

Pertinent Service Project
AN-29

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National Defense Research Committee

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Volume 6. September 5, 1945

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Pertinent Service Project
AN-29

Approved on September 18, 1945
for Division 2 by

Ralph J. Slutz

R. J. Slutz, Technical Aide
Division 2
Effects of Impact and Explosion

C O N F I D E N T I A L

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Preface

The present volume is the sixth of a series of monthly reports on the damage capabilities of military weapons. In it the Weapon Effects Group, Princeton University Station, Division 2, reports on its investigation of the vulnerability of targets to attack by airborne weapons and on studies prepared for its loose-leaf volume "Weapon Data -- Fire, Impact, Explosion."

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. Loose-leaf copies of the individual papers are available for distribution to those authorized to receive material on only specific parts of the work described.

The work described in this report is pertinent to the project designated by the War and Navy Department Liaison Officers as AN-29. The work was performed under Division 2 Contract OEMsr-260 with Princeton University.

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CONTENTS

Monthly Report EWT-6a (OSRD-5657a)
September 5, 1945
Division 2, NDRC

Project AN-29

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

Princeton University
W. Bleakney, Supervisor

ATTACK ON OPEN GUN EMPLACEMENTS

by R. H. Dietz

Abstract

Open gun emplacements may be attacked by bombs delay-fuzed for earthshock and cratering effect or by bombs fuzed instantaneously for fragmentation effect. Values of the mean area of effectiveness of bombs used against various guns are given in Table I. In order to determine the most efficient bomb for attack on a gun emplacement of known size, comparison of values given in the table should be made. Since damage to auxiliary equipment such as ammunition storage, command posts, range finders, communications, and so forth, by cratering bombs can cause a reduction in firepower not directly attributable to gun unserviceability, the mean area of effectiveness for fragmentation bombs must in general be $1\frac{1}{2}$ to 2 times as great as that for cratering bombs for equal reduction in firepower by the same bombing density.

1. Introduction

This paper deals with the vulnerability of guns to the effects of various sizes and kinds of bombs. It attempts to show the relative mean areas of effectiveness of the bombs for fragmentation and earthshock against guns, thereby aiding in the selection of the best bomb to be employed, and it recommends the method by which the greatest degree of damage may be attained. It must be understood that no attempt is made to evaluate the bomb or bombs for various plane loadings and methods of dropping.

2. Gun positions and batteries

(a) Emplacements. -- Only guns in the open and in revetted emplacements are considered here. The revetments may vary from 15 ft to 60 ft in diameter with an average inside height of $4\frac{1}{2}$ ft. The construction of emplacements has been used to separate them into two types: those with reinforced concrete incorporated in the base plate and the parapet walls, and those employing stone and mortar, earth, earth and logs, or sandbags.

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(b) Supporting equipment. -- The term "supporting equipment" is interpreted to cover those ancillary pieces necessary for satisfactory functioning of a gun or battery of guns.

The predictor, range finder, and tracking instruments, whether mechanical or electrical, are thought of as targets vulnerable to all forms of bomb damage; that is, earthshock, debris, and fragmentation. Occasionally the control post falls in this category. Other equipment, such as ammunition storage and shelters, should not be considered as fragmentation targets, but subject to damage only by earthshock or cratering.

(c) Guns. -- For the purpose of this study guns have been divided into three classes: light (20-mm to 37-mm); medium (75-mm to 120-mm); and heavy (150-mm and larger).

Certain parts of guns are more vulnerable to damage than others either by earthshock or fragmentation. The particular parts damaged will in most instances be the factor determining how long the gun will be out of operation. Attempts have been made1/ to evaluate the vulnerable area of guns to fragmentation by relating this area to an equivalent area of either 1/8, 1/4, or 1/2 in. of mild steel, the presentation area depending on the various aspects of the gun. This equivalent area of steel should only be used for unshielded guns, unless due consideration is given to those vulnerable parts shielded and the equivalent area for these is subtracted from the probable average area for the unshielded gun.

For the purpose of this paper guns having as much as three-fourths of the vulnerable components shielded by armor from $\frac{1}{2}$ to $1\frac{1}{2}$ in. in thickness are considered as not vulnerable to fragmentation bombs except in the case of a direct hit. Lightly shielded guns, employing armor $\frac{1}{4}$ in. and less, are considered completely exposed to fragmentation. No attempt has been made to isolate individual guns for vulnerability, since the data do not warrant such analysis; therefore, the equivalent steel area is thought of collectively and is applied to all guns of a class such as all medium guns.

1/ "Vulnerability of guns to attack by bombs and shell," Army Operation Research Group Report No. 288 (British).

3. Causes of damage

(a) Cratering and debris. -- When a cratering bomb damages a gun it may do so by direct damage to the gun and position (effects of the explosion) or by indirect damage (effects of flying debris).

(i) Direct damage, or that damage resulting in the fracturing of the baseplate or the tossing of the gun about in the emplacement, will, in practically all cases, render the gun unserviceable.[2/]

(ii) Damage from flying debris will vary from unserviceability to that requiring minor repairs.[3/] This is generally attained by debris damaging some portion of the mechanism required for operation or by enveloping the gun in debris to such an extent as to require cleaning before firing can be resumed.

(b) Fragmentation. -- Damage to guns by fragmentation is the direct result of a fragment or number of fragments damaging a component part of the gun which will make it inoperative. Although all parts of the gun are vulnerable to some given size of fragment at a limiting distance, the parts most frequently found damaged are the following:

recuperator,	sights,
buffer,	leveling devices,
traversing gear,	tube,
breech,	cradle,
elevating gear,	trails.

Probably the most vulnerable part of any gun is the recuperator coil assembly which also may house the buffer. The types of damage may vary from unserviceability to minor damage depending upon the availability of spare parts and repair facilities.

2/ "Unserviceable damage" is defined as requiring shop repair or putting the gun out of action for more than 24 hours.

3/ "Temporarily unserviceable or minor damage" is defined as putting the gun out of action for less than 24 hours.

4. Reduction in firepower

In the analysis of Operation Corkscrew[4/] it is assumed that for anti-aircraft batteries the reduction in firepower and operational efficiency due to destruction of the supporting equipment will be approximately 50 to 80%. Similarly, these same conditions are assumed to prevail for coast defense guns except that the efficiency reduction may be only 30 to 50%. Data from the afore-mentioned report indicates that for delay-fuzed GP bombs, the guns attacked may be damaged to an extent of 30% of normal operation, that the supporting equipment may be damaged to an extent of 45%, and that the reduction in firepower might be 60%. Although approximately 54% of the guns attacked on Pantelleria were damaged either permanently or for a short time this does not represent a real interpretation of the reduction in firepower; actually only about 12% of the guns were permanently destroyed.

Reduction in firepower may mean the inability to coordinate fire, inaccuracies in aiming, reduction in the number of rounds that may be fired, or complete destruction of the position.

5. Damage to supporting equipment

Damage to supporting equipment must be considered as a contributing factor, since its influence on the density of bombs required proved appreciable. For example, let us assume that the MAE for a given bomb is the same for both fragmentation and earthshock and also assume as a basis of calculation that a 45% reduction in firepower is required for neutralization of a given battery. This reduction in firepower by fragmentation damage requires that 45% of the guns be made unserviceable. However, in an attack with cratering bombs if only 30% of the guns are destroyed a total reduction in firepower of 45% will result, the balance being attributed to loss of firepower due to damage of control equipment. Thus to attain equal reduction in firepower for the respective bombs the levels of gun damage for cratering and fragmentation bombs are 30 and 45%. The fraction F of the target damaged for bombs having an MAE, M, and covering the target with a density D is $F = 1 - e^{-MD}$. Thus for comparing fragmentation bombs (subscript f) and

4/ "Operation 'Corkscrew' -- Analysis of relation between bomber effort and effects achieved," by S. Zuckerman, July 20, 1943. PF-1904/53 (Secret).

cratering bombs (subscript c)

$$\frac{F_f}{F_c} = \frac{1 - e^{-M_f D_f}}{1 - e^{-M_c D_c}},$$

or

$$\frac{D_f}{D_c} = \frac{M_c \log(1 - F_f)}{M_f \log(1 - F_c)}.$$

For $F_f = 0.45$, $F_c = 0.30$, $M_c = M_f$ as assumed above, we find $D_f/D_c = 1.68$. This means that to attain the same reduction in firepower from fragmentation as from earthshock or cratering, 68% more bombs are required. Similar calculations may be made for various values of M_f and M_c.

If the density were held constant and equal, the MAE for fragmentation would have to be increased by 68% to attain the same reduction in firepower as from earthshock or cratering. This would indicate that the additional damage accrued from the effect of cratering bombs is appreciable.

6. Mean area of effectiveness (cratering and debris)

When considering the MAE due to cratering and debris caused by delay-fuzed bombs (0.025 and 0.01 sec delay), the effect from fragmentation must be neglected. The damage must be attributed either to cratering, which may cause structural damage, or to debris, which may cause mechanical damage.

The MAE's obtained for delay-fuzed bombs are for what might be called average soil, giving lower values than those found by Zuckerman on Pantelleria. The difference may be attributed to the rocky nature of the soil there since the resultant rocky debris will produce more effective damage.

(a) Medium guns. -- The data used in arriving at the MAE's were for 500-lb and 1000-lb GP bombs fuzed 0.025 sec against medium guns ranging from 75-mm AA to 155-mm AA/CD guns found in Southern and Northern France.[5]

5/ "Observations of results of aerial bombardment and other items of military interest in Southern France," Army Air Forces Evaluation Board Report, Mediterranean Theatre of Operations, 18 November 1944. "Close-in air cooperation with the ground forces at Le Havre, France," AAF Evaluation Board in the ETO, 5 April 1945. "Bomb damage survey of pre-invasion targets in Southern France," Ordnance Section, Twelfth Air Force, 30 September 1944. "Report to 21st Army Group on the bombing of targets in the British sector, Normandy," REN 415, Ministry of Home Security.

These data indicate that for guns to be made unserviceable the MAE for an average bomb of 750 lb, determined by graphical integration of $rP(r)$ against r (see Figs. 2 and 3) where r is the distance of the bomb hit from the center of the gun and $P(r)$ is the probability of damage, is 950 ft^2. The MAE for temporary unserviceability was found to be approximately 6000 ft^2.

If these empirical values are the result of cratering and its resultant effects the radius of damage should be proportional to $w^{1/3}$ and the area proportional to $w^{2/3}$ where w is the weight of explosive charge in the bomb. For average soil conditions and for the assumed average bomb of 750 lb and charge/weight ratio of 50% (as in the average GP bomb), the crater area would be approximately 1000 ft^2. This is a close approximation of the empirical value of 950 ft^2 for complete unserviceability. For temporary unserviceability for an average bomb we have found the MAE to be 6000 ft^2, so the radius for damage is $\sqrt{6000/1000}$ = 2.4 times the crater radius. The MAE for temporary unserviceability for the 500-lb and 1000-lb GP bombs is approximately 6 times the area of crater for these bombs. Assuming that this relation may be applied to the smaller GP bombs, the MAE values for the respective bombs are as given in Table I.

(b) Light guns (20-mm to 37-mm). -- It is assumed that light guns can be rendered unserviceable at approximately 2 crater radii and temporarily unserviceable at 4 crater radii. This is indicated by incidents where such guns have been rendered unserviceable at distances of 25 to 30 ft by the 500-lb GP.6/ This also agrees with the results of trials carried out with 500-lb M.C. bombs (British) buried in clay and chalk at a depth corresponding to 0.025-sec delay fuzing.7/ The MAE values determined in this way are given in Table I.

7. Mean area of effectiveness (fragmentation)

MAE's for fragment damage are defined exactly as other MAE's by means of an integrated probability, in this case the probability of damage of the

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6/ "Bomb damage survey of pre-invasion targets in Southern France," Ordnance Section, Twelfth Air Force, 30 September 1944.

7/ "Distribution of crater debris in clay and chalk," R.C. 409, Ministry of Home Security. (British).

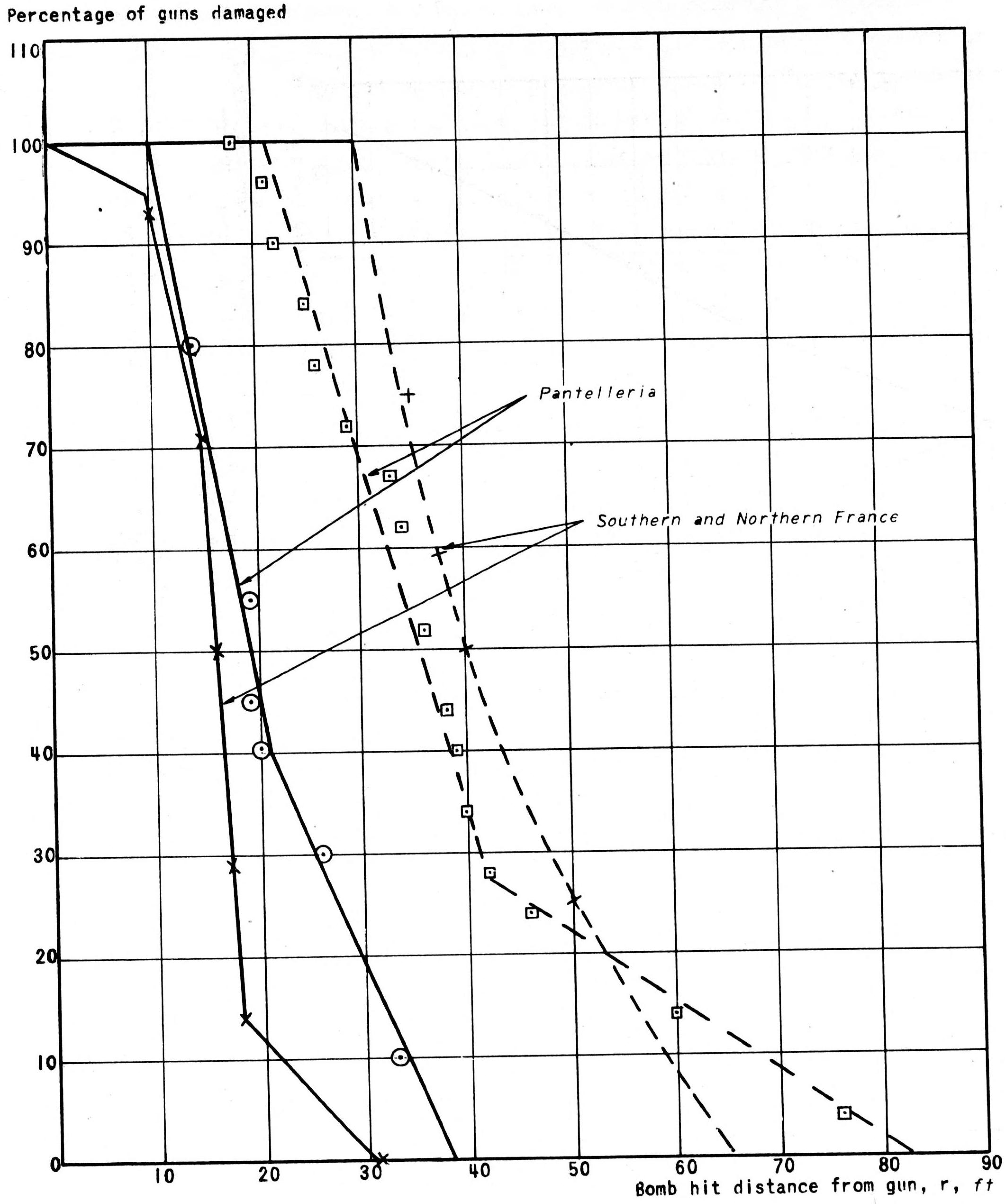
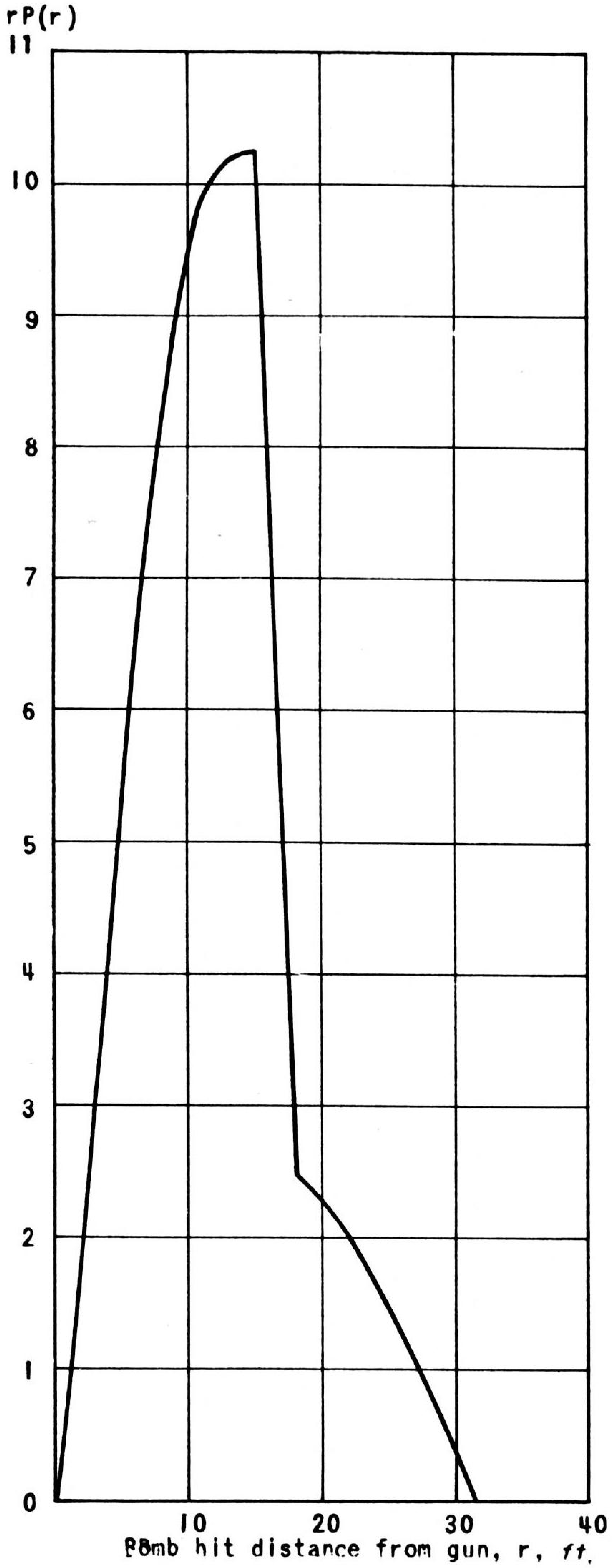


Fig. 1. Guns damaged by bomb hits at various distances
Solid line = Unserviceability
Chain line = Temporary unserviceability



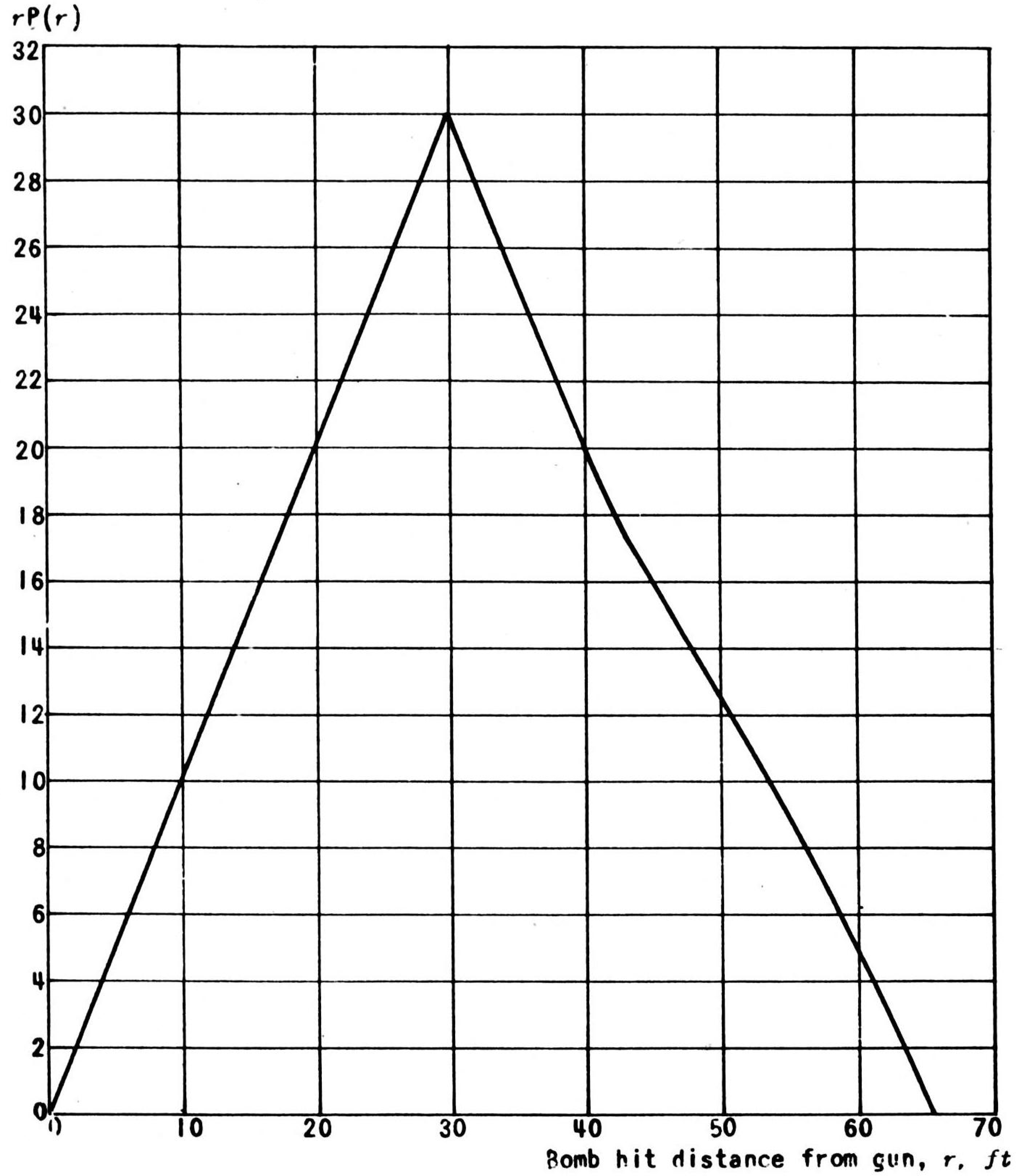


Fig. 3(above). rP(r) versus r for temporary unserviceability of guns, Southern and Northern France. Area under curve = $957\frac{1}{2}$ ft^2. M A E = $957\frac{1}{2} \times 2\pi$ = 6020 ft^2.

Fig. 2(left). rP(r) versus r for unserviceability of guns, Southern and Northern France. Area under curve = 150 ft^2. M A E = $150 \times 2\pi$ = 943 ft^2.

Princeton University Station
Division 2 NDRC

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Table I. Mean area of effectiveness per bomb for various bombs against unshielded guns.

Type of Damage	Bomb	Crater Radius (ft)	Fuzing (sec)	Light Guns*: MAE for Unserviceability** (ft^2)	Light Guns*: MAE for Temporary Unserviceability** (ft^2)	Medium and Heavy Guns*: MAE for Unserviceability** (ft^2)	Medium and Heavy Guns*: MAE for Temporary Unserviceability** (ft^2)
Earthshock (guns revetted or in open)	100-lb GP AN-M30	9.25	1/100	1000	4300	270	1600
	250-lb GP AN-M57	12.0	or	1800	7200	450	2700
	500-lb GP AN-M64	15.5	1/40	3000	12000	750	4500
	1000-lb GP AN-M65	19.75		4900	19600	1200	7300
Fragmentation (guns in open)	20-lb F AN-M41		Inst.	Data do not warrant prediction for these guns		300	600
	20-lb Para.Frag.					300	600
	90-lb F AN-M82					2400	4800
	100-lb GP AN-M30					3700	7400
	260-lb F AN-M81					7000	14000
	500-lb GP AN-M64					10400	20800

Type of Damage	Bomb	Fuzing	Light Guns*: 20	30	40	50	60	Medium Guns*: 20	30	40	50	60
	Diameter of Emplacement (ft) →		MAE for Unserviceability** (ft^2)									
Fragmentation (guns in revetments)	20-lb F AN-M41	Inst.	300	--	--	--	--	300	--	--	--	--
	20-lb Para. Frag.	Inst.	300	--	--	--	--	300	--	--	--	--
	90-lb F AN-M82	Inst.	600	1100	1800	2600	3600	600	950	1500	2000	2300
	100-lb GP AN-M30	Inst.	600	1100	1800	2600	3600	600	1100	1800	2400	3200
	260-lb F AN-M81	Inst.	600	1100	1800	2600	3600	600	1100	1800	2600	3200
	500-lb GP AN-M64	Inst.	600	1100	1800	2600	3600	600	1100	1800	2600	3200
	500-lb GP AN-M64	VT	10400	10400	10400	10400	10400	10400	10400	10400	10400	10400
	500-lb GP AN-M64	VT	***	***	***	***	***	***	***	***	***	***

* Guns are classified as light (20 mm to 37 mm), medium (75 mm to 120 mm), and heavy (150 mm and larger).

** Unserviceability means damage requiring shop repair or more than 24 hr field repair. Temporary unserviceability means unserviceable but repairable in less than 24 hr.

*** MAE for temporary unserviceability for all revetted guns is 20800 ft^2.

specified degree by fragments. The MAE's estimated in this report for fragment damage to guns cannot be regarded as very reliable: the data for the experimental determination of such MAE's are scanty, and the assumptions going into the theoretically determined MAE's are questionable. This section indicates the methods used in arriving at the estimates in Table I pertaining to fragmentation.

(a) Guns in the open. -- For light guns the amount of relevant data available was insufficient even for very rough estimates of MAE's.

For medium and heavy guns the "unserviceability" MAE of 10,400 ft² for the 500-lb bomb is that experimentally determined in bombing trials at Ashley Walk against 18-pounder guns.8/ The "unserviceability" MAE's for the other bombs, excluding the 20-lb bombs, were obtained by multiplying by a constant the MAE's9/ given in T.D.B.S. Report No. 49 for the bombs against elementary targets consisting of 2 ft² of ¼-in. mild steel. The constant was determined by equating the result thus obtained for the 500-lb bomb to the Ashley Walk figure. The "unserviceability" MAE for the 20-lb bombs is estimated from a small amount of data in a Fifth AAF report.10/ All these MAE's were doubled to give those for "temporary unserviceability"; the basis for this is the ratio of the corresponding Ashley Walk estimates for the 500-lb bomb, namely 25,200/10,400. It should be remarked that the guns in the Ashley Walk trials were obsolete affairs with wooden wheels and presumably more susceptible to temporary damage than more modern guns. It should also be made clear that by "temporary unserviceability" we mean "temporary unserviceability or worse."

(b) Guns in emplacements. -- For the 20-lb bombs against light, medium, or heavy guns in emplacements 20 ft in diameter, the source of the estimate is the same as in the last subsection.10/ For the 20-lb bombs and larger emplacements, the data were considered insufficient.

For other bombs, excluding the 500-lb GP with VT fuze, the MAE listed for light guns is simply the area of a circle whose radius exceeds that of

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8/ "Attack of guns," Ord. Board Proc. Q 2642, by B. L. Welch. (British).

9/ Called "damage expectancies E" in loc. cit.

10/ "Effect of bombs on Jap heavy ack-ack," Ordnance Technical Report, Fifth Air Force, 12 July 1944.

the emplacement by 4 ft. This is equivalent to the assumption that a bomb landing inside the emplacement is certain to render a light gun unserviceable, together with an allowance of a 4-ft margin for edge effects. The MAE estimated for these bombs against medium and heavy guns was calculated from the formula

$$MAE = 2\pi \int_0^R \left[1 - e^{-S\rho(r)}\right] r \, dr,$$

where $\rho(r)$, obtained from TM9-1907,11/ is the average density (fragments/ft^2) of fragments capable of perforating $\frac{1}{4}$ in. of mild steel at distance r from the bomb; S[= 4 ft^2] is the presentation area assumed for an equivalent elementary target; and R is the emplacement radius increased by 4 ft for edge effect.

The MAE's for the VT fuzed 500-lb bomb against all types of guns in all sizes of emplacements were assumed equal to those of the same bomb when ground-burst against heavy and medium guns in the open.

11/ "Ballistic data, performance of ammunition," War Department, Technical Manual TM9-1907.

Monthly Report AWT-6b (OSRD-5657b)
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Project AN-29

Princeton University
W. Bleakney, Supervisor

MAE'S CALCULATED FROM ASHLEY WALK FRAGMENTATION TRIALS

by Henry Scheffé

Abstract

Mean areas of effectiveness for fragmentation damage to several targets are obtained from data in O.B. Proc. No. Q 2390 and Q 2881. The results are summarized in Tables I and II.

Table I. MAE for substantial damage by ground-burst bombs.

Bomb	MAE (ft^2) for Substantial Damage to		
	Aircraft	Mechanical Transport	Personnel, Prone, Unshielded
British 500-lb M.C.	79,000	44,000	24,000
British 250-lb M.C.	45,000	21,000	22,000
Cluster of 20-lb, American M41, 18 firing*	110,000	100,000	90,000

*Dropped with "parasheets."

Table II. MAE for substantial damage by American 500-lb GP bomb, air-burst.

Target	MAE (ft^2) for Substantial Damage	
	Avg. Height of Burst, 36 ft	Avg. Height of Burst, 10 ft
Men in deep trenches	4800	5200
Men in shallow ditches	8000	5600
Men prone without cover	24000	25000
Mechanical transport	16000	38000

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1. Ashley Walk trials

The great value of the Ashley Walk trials lies in the fact that they were direct experimental measurements of the effectiveness of bombs against actual targets (except for personnel, for which wooden dummies were substituted) when the bombs were dropped under operational conditions. This eliminates many of the questionable links in the chain of reasoning to the same goal from static experiments against sand pits and a ring of wooden panels. The reader is referred to the original papers for details as to targets, operational conditions, and so forth.

2. Results

Table I, giving MAE's of British 500-lb M.C. and 250-lb M.C. bombs, and clusters of American 20-lb fragmentation bombs for substantial damage to aircraft, mechanical transport, and prone troops in the open, is calculated by Eq. (1) which follows, taken from O.B. Proc. No. Q 2390.[1,2] "Substantial damage" is defined as follows. For aircraft: complete destruction, or damage requiring more than 10 man-days for repair. For mechanical transport: damage involving write-off or requiring repair at a second echelon or base workshop. For personnel: incapacitation.

It should be noted in Table I that the results for the 500-lb M.C. and the 250-lb M.C. bombs do not conform to a scaling law to the effect that the MAE varies as the 2/3 power of the weight.

Table II gives MAE's of American 500-lb bombs with T50 fuzes against troops and mechanical transport. These MAE's are quoted from O. B. Proc. No. Q 2881[3] and were checked by Eq. (1). By the method explained in the following, rough estimates of the standard deviations of these MAE's were calculated; these ran around 20% of the MAE. No estimate of error could be made for the MAE's in Table I since Proc. No. Q 2390 does not give the number of targets exposed to risk, but only the proportions damaged -- the p_i in the notation used in the following.

1/ If desired, the corresponding MAE's for clusters of 8 British 40-lb GP's and clusters of 26 British 20-lb frag bombs could also be obtained from the data in this report.

2/ "Relative efficiency of various bombs with alternative fuzing against close support targets," O.B. Proc. No. Q 2390. PF-3330/31.1.

3/ "Trials with an M 64 500-lb bomb nose initiated against close support targets," O.B. Proc. No. Q 2881 and appendices. PF-3330/31.2.

3. Method of calculation

The method of calculation is as follows. Let the ground around the bomb or cluster be divided into zones of area A_i ($i = 1, 2, \ldots$), let n_i be the number of targets exposed to risk, and let p_i be the proportion receiving the specified degree of damage. The MAE is calculated from the formula

$$MAE = p_1 A_1 + p_2 A_2 + \ldots. \qquad (1)$$

In greater detail, the calculation for individual bombs is made thus. Choose a set of radii $r_1, r_2, \ldots$.[4/] With the jth bomb as center (if the bomb is air-burst, the point on the ground below the bomb as center) draw the circles of radius r_i. Let n_{ij} be the number of targets exposed to risk in the ith ring lying between the radii r_{i-1} and r_i (take $r_o = 0$), and let x_{ij} be the number damaged in this ring by the jth bomb.

Then the p_i, A_i, n_i introduced in the foregoing are defined by

$$p_i = \sum_j x_{ij} / \sum_j n_{ij},$$

$$A_i = \pi(r_i^2 - r_{i-1}^2),$$

$$n_i = \sum_j n_{ij}.$$

For clusters the areas in Fig. 2 of Proc. No. Q 2390 were planimetered to get the A_i.

If the number $n_i p_i$ damaged in the ith zone were distributed according to a binomial distribution with probability π_i, then the quantity defined in Eq. (1) would have a variance given by the formula

$$\sum_i \sum_j A_i A_j \rho_{ij} \left[\pi_i \pi_j (1 - \pi_i)(1 - \pi_j)/n_i n_j\right]^{\frac{1}{2}}, \qquad (2)$$

where ρ_{ij} is the correlation coefficient between p_i and p_j. If we ignore the off-diagonal terms in formula (2) we get

$$\sum_i A_i^2 \pi_i (1 - \pi_i)/n_i. \qquad (3)$$

Formula (3) could be regarded as a good approximation to formula (2) if we could convince ourselves of the plausible assumption that the correlations

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4/ In Proc. No. Q 2390, $r_i = 50\,i$ ft for $i = 1,2,3,4,5,6$. In Proc. No. Q 2881, $r_1 = 50$ ft, $r_2 = 100$ ft, $r_3 = 200$ ft, $r_4 = 300$ ft.

ρ_{ij} $(i \neq j)$ are negligible, or else we may regard formula (3) as an indication of the order of magnitude of formula (2). Finally, an unbiased estimate of formula (3) may be shown to be

$$\sum_i A_i^2 p_i(1 - p_i)/(n_i - 1), \tag{4}$$

and the square root of this was used to estimate the standard deviation mentioned above.

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September 5, 1945
Division 2, NDRC

Project AN-29

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Princeton University
W. Bleakney, Supervisor

TESTS OF INTERNAL EXPLOSION ON OIL STORAGE TANKS

by J. A. Wise

Abstract

Tests made on four model steel oil storage tanks, containing oil and subjected to an internal explosion, agree with the prediction that the charge required to produce rupture, when tanks are full, is given approximately by $w = 3\ tr^2$ where w (lb) is the weight of explosive, t (in.) is thickness of shell, and r (ft) is distance from point of explosion to nearest surface of tank. When tanks are partly full a somewhat larger charge would be required to produce destruction, although the charge determined by the above formula would produce some damage. The effect of efficiency of riveted joints is approximated by multiplying actual thickness of plates by efficiency of joint to obtain an equivalent thickness for use in the above formula. It is also concluded that, for equal stowage efficiency of various bombs on aircraft, the 100-lb GP bomb is the most efficient weapon. For the usual steel oil storage tank, any GP bomb should penetrate without breakup if dropped from an altitude of at least 3000 ft.

1. Previous studies

A previous study[1] of the subject was based on experimental data obtained from internal explosions in a water-filled steel pipe.[2] In reference 2 the internal charge at the center required to rupture a water-filled steel pipe was obtained theoretically by a consideration of the energy released by the explosion, and the formula thus derived was checked experimentally. This was applied, in reference 1, to steel oil storage tanks and it was noted therein that no account had been taken of the effect of using oil instead of water, of the effect of the top and bottom of the tank in limiting the length of "pipe," and of the effect of partial filling of tanks. In order to verify

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1/ "Effect of internal explosions on oil storage tanks," EWT-2a (OSRD-5045a), Division 2, NDRC, May 1945.

2/ "Internal explosion in water-filled pipe," OTB-9m (OSRD-4948m), Division 2, NDRC, April 1945.

C O N F I D E N T I A L

the conclusions in that study concerning the charge required to produce rupture, a series of tests on model steel oil storage tanks containing oil was made.

2. Model tanks and procedure

Four model tanks were constructed as shown in Fig. 1. These tanks were approximately 1/10 scale of 60-ft prototypes. They were imbedded in a 3-in. concrete slab set on the ground, and were spaced on about 25-ft centers, in one line.

"Forum" oil, number 40, having a specific gravity of 0.88 and a Saybolt viscosity at 100°F of 114 sec, was used. This is an oil used for painting wood forms for concrete work. Tanks 1 and 2 were filled with the oil and tanks 3 and 4 were about half full.

The charge used in each test was one 22-gm pellet of Tetryl, detonated by a No. 6 electric cap. In tanks 1 and 3 the charge was on the vertical center line of the tank, in tanks 2 and 4 the charge was placed about 1 ft from the side. In tanks 1 and 2 the charge was placed 1 ft below the top of the tank, and in tanks 3 and 4 it was placed at mid-depth of oil.

High-speed motion pictures (about 4000 to 6000 frame/sec) and colored motion pictures at 24 frame/sec, Fig. 2, were taken of the tests.

After the tests were completed, coupons were cut from the tanks, two of the solid sheet steel and five across joints, and these were tested for tensile strength.

3. Experimental results

The explosion on the center line 1 ft below the top of tank No. 1, which was filled, resulted in the destruction of the top of the tank and the rupture of seams in the sides [Fig. 2(a)]. The circular seam about half way from edge to center of the top was ripped open and the central portion was thrown upward hinging like a flap on one small neck of metal. The radial seams in the top were also ripped open. The vertical seams in the side were ripped in several places, but the high-speed pictures showed that the lateral seams began to rip only after the top started to open. The oil was released and gushed from the tank. The whole tank was lifted about 6 in. from the base. This tank was considered to be destroyed.

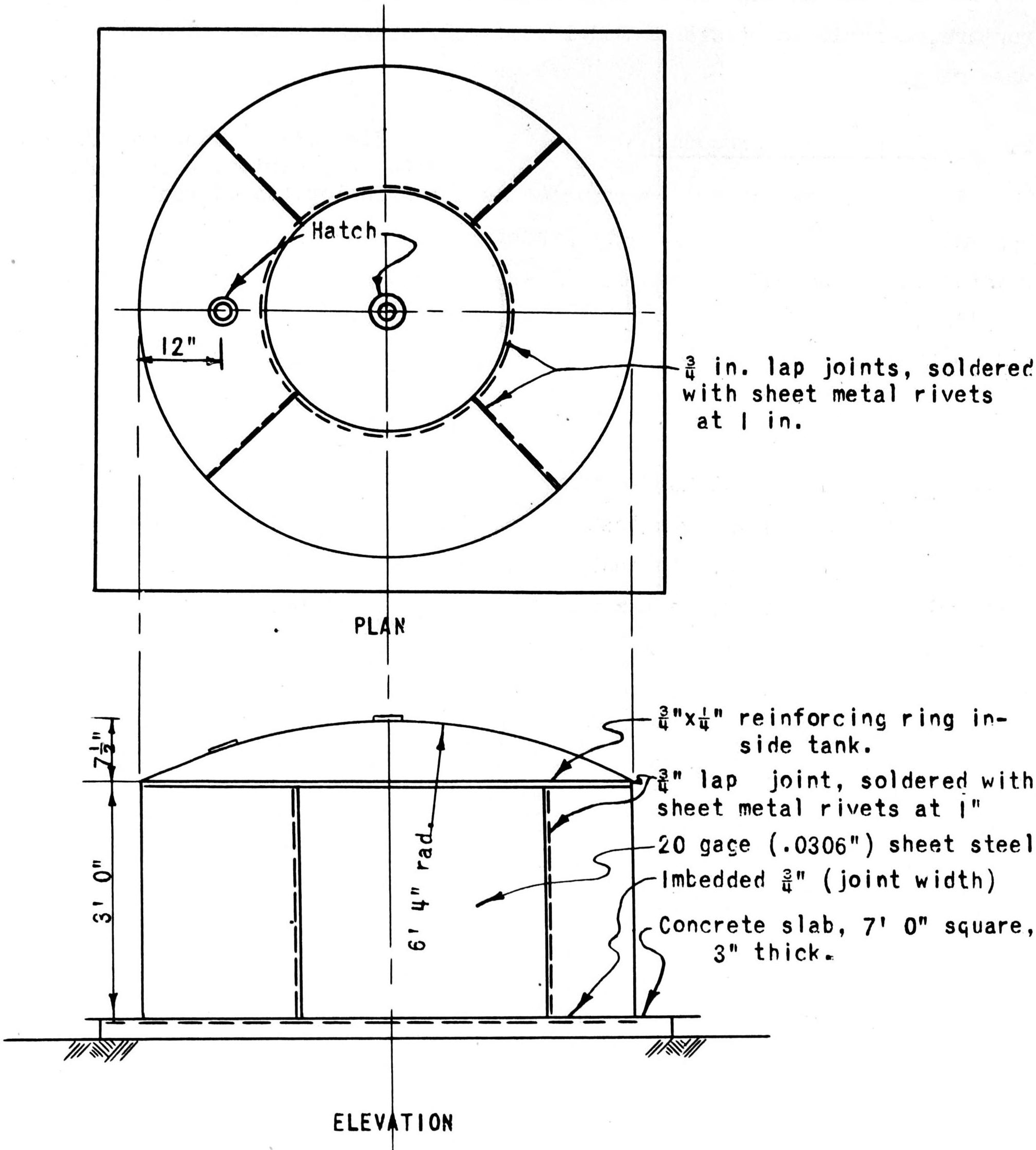

FIG. 1. MODEL OIL STORAGE TANKS.

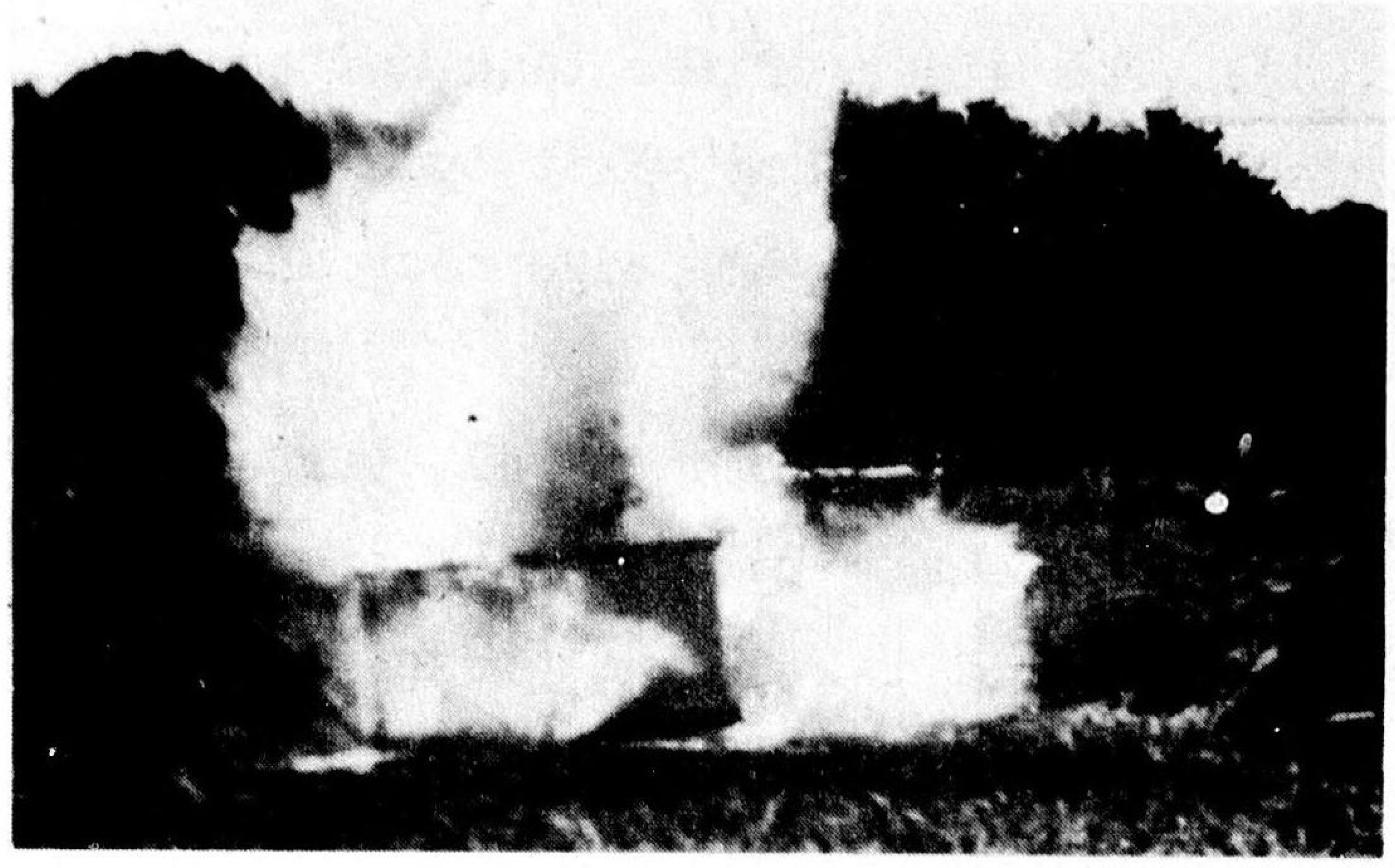

Fig. 2(a). Tank No. 1, filled with oil, explosion on center line 1 ft below top of tank.

Fig. 2(b). Tank No. 2, filled with oil, explosion 1 ft from edge.

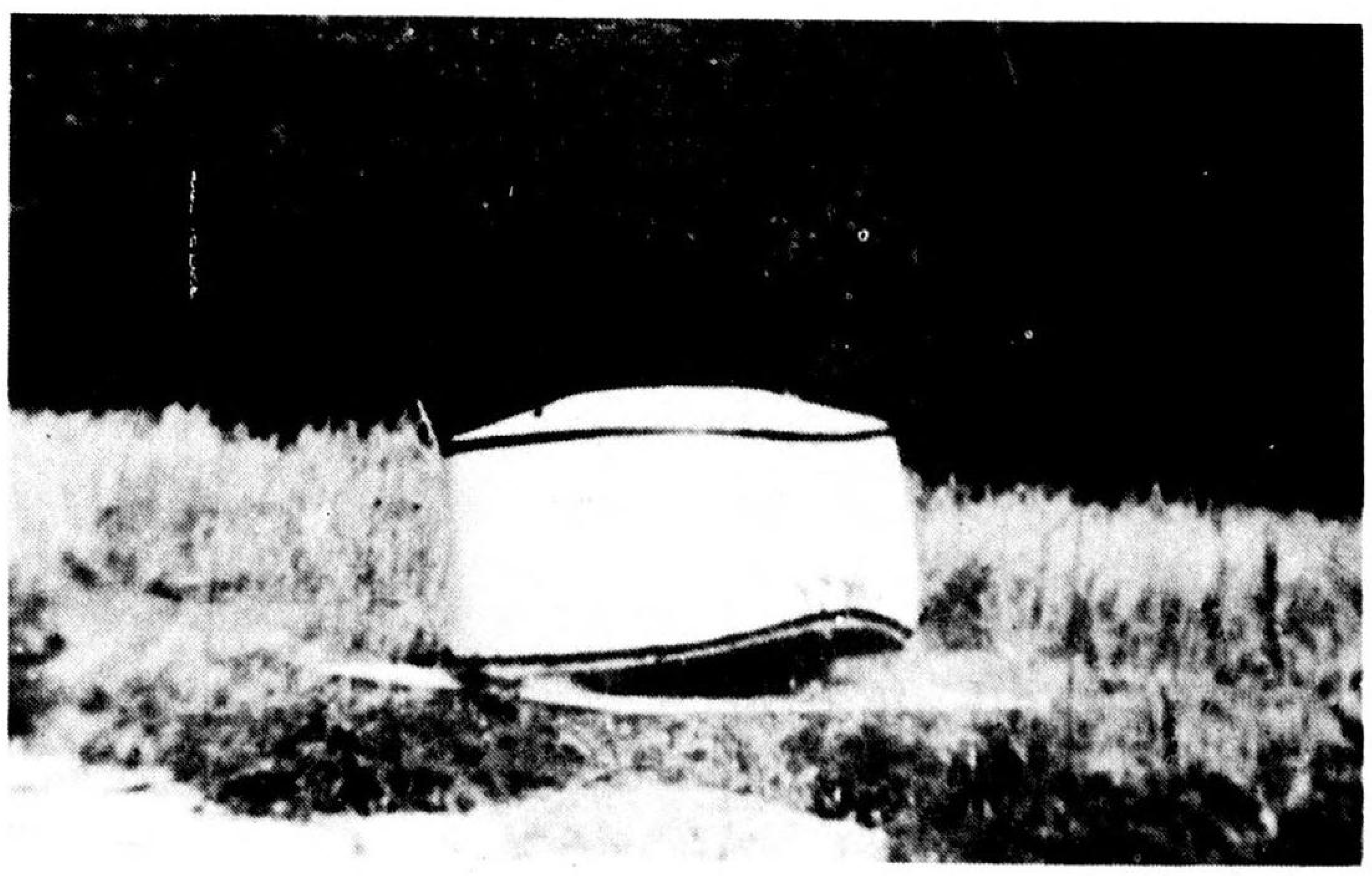

Fig. 2(c). Tank No. 4, half-filled with oil, explosion 1 ft from edge.

Tank No. 2, which was filled, was also destroyed by the explosion of a charge 1 ft from the edge [Fig. 2(b)]. The sides of the tank and top edge near the explosion suffered the greatest damage. Seams split open and released the oil. The tank lifted about 6 to 8 in. at the edge near which the charge was detonated.

The half-filled tank No. 3 with charge at mid-depth of oil, was destroyed by the explosion in the center. The vertical seams in the sides opened and oil spurted out. The top of the tank was sucked inward and presented a partly collapsed appearance. Apparently the oil and some air were ejected rapidly from the interior through the side seams and the side walls moved outward so that, on the suction phase of the blast, the area of openings in the side was insufficient to admit air returning to the tank and as a result, the internal pressure became less than atmospheric. This tank lifted bodily about 18 in.

Tank No. 4, half full of oil, was damaged but not destroyed by the explosion of a charge 1 ft from the edge [Fig. 2(c)]. One seam at the lower edge near the charge opened and allowed a small flow of oil. That edge had lifted about 30 in. as a result of the explosion and may have been cracked open on striking the concrete slab.

Since the earth's gravitational pull was not scaled down in the model, the phenomenon of the lifting of the tanks was not in scale. However, the relative motion of certain points of the model was measured from the high-speed motion pictures. This motion is shown graphically in Fig. 3. These graphs indicate that the top center portion of the tank ruptured first and began to move with a fairly high velocity, while the rest of the top, freed from the restraint of the center portion, moved with a much lower velocity.

Tension coupons $1\frac{1}{2}$ in. wide were cut from the tanks after the test; two from the solid metal and five across seams. Tension tests of these gave the ultimate strength of the steel as 54000 lb/in.^{2} and the efficiency of the joints (based on ultimate strength) as 64%.

4. Analysis of results

The formula presented in reference 1,

$$w = 3\ tr^2, \tag{1}$$

where w (lb) is the weight of charge required for rupture, t (in.) is

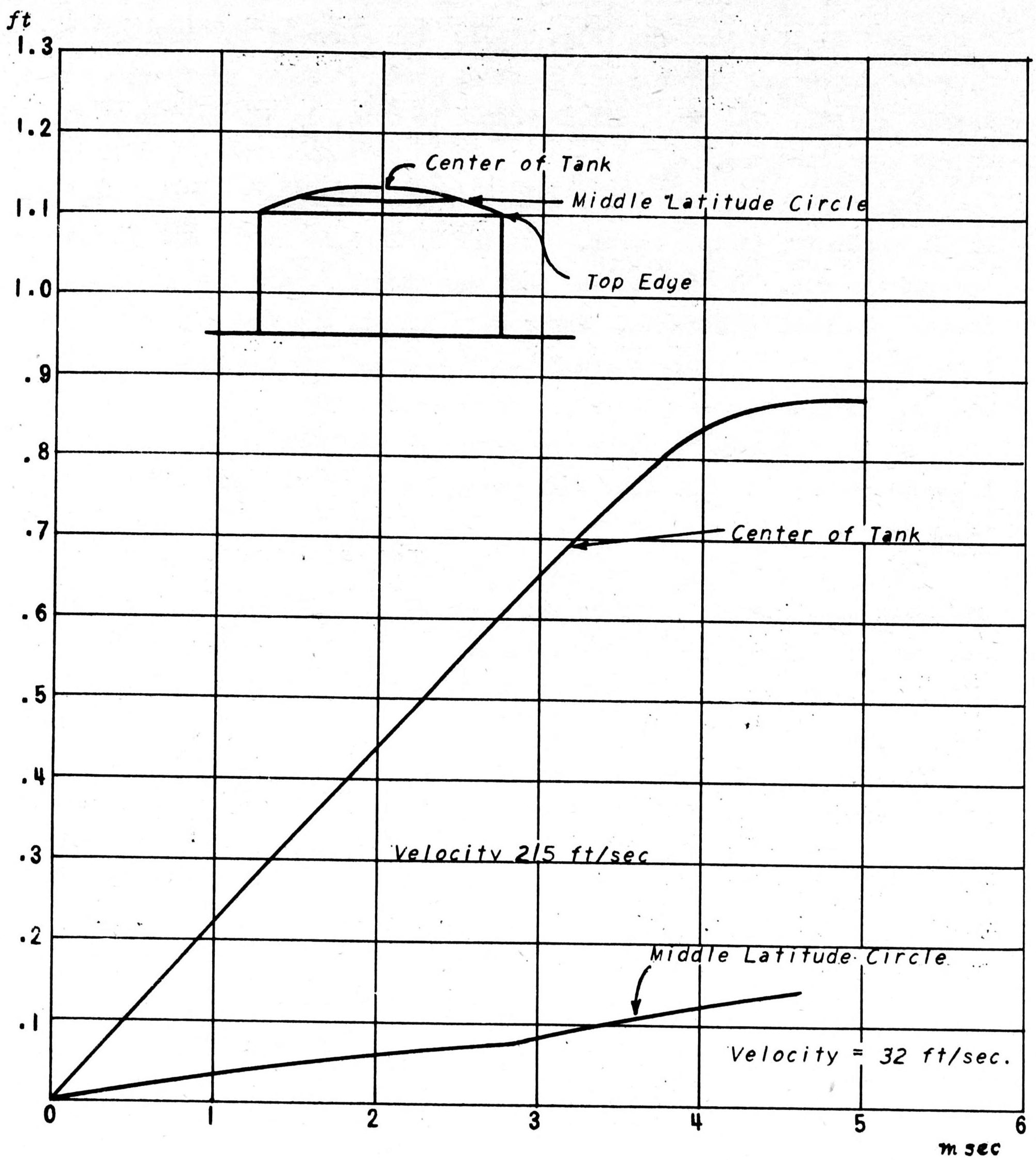

FIG. 3. MOTION RELATIVE TO TOP EDGE OF POINTS ON TOP OF TANK.

thickness of shell, r (ft) is distance from charge to nearest point of tank, appears to give satisfactory results in this test.

Since Tetryl was used instead of TNT, the weight of charge used was multiplied by 1.1, an estimated factor for conversion of Tetryl to an equivalent amount of TNT. The actual thickness (0.0306 in.) was multiplied by the efficiency of joints (64%) to obtain the equivalent solid metal thickness. Then, with w equal to 22 gm, or 0.0485 lb,

$$r = \sqrt{\frac{0.0485 \times 1.1}{3 \times 0.0306 \times 0.64}} = 0.95 \text{ ft.}$$

In the test, the distance r at which breakage occurred was 1 ft. However, when the tank is only partly full, the effect of the explosion is less severe and a somewhat larger charge would be required to produce certain destruction. The results for the partly full tanks were erratic in that a charge 1 ft from the side produced less damage than the one at the center, which was about 3 ft from the side wall. This phenomenon remains as an unexplained anomaly ascribable to the small number of tests made.

5. Conclusions

Scaling to prototype size, a charge of 0.0485 × 1.1 × 1000 = 53 lb of TNT would be required to rupture a 60-ft diameter tank when detonated within about 10 ft of the tank wall. This means that a 100-lb GP bomb should suffice. The top of the tank will be ruptured if the bomb detonates within critical distance.

When bombs are dropped from high altitudes, they may penetrate the top of the tank and detonate at a distance such that the top may not be ruptured. However, there is always a chance that they may detonate within vulnerable distance of the side walls, and may thus destroy the tank. Consider the plan view of a tank, Fig. 4, with outside radius R, and vulnerable distance r, for a given bomb of weight W.

The vulnerable area, shaded in the figure, is an annulus of area

$$A = \pi R^2 - \pi(R - r)^2 = \pi(2Rr - r^2). \tag{2}$$

The angle of impact, α, may be such that ricochet will occur if it strikes the side of the tank. In that case a small area (shown doubly shaded) must

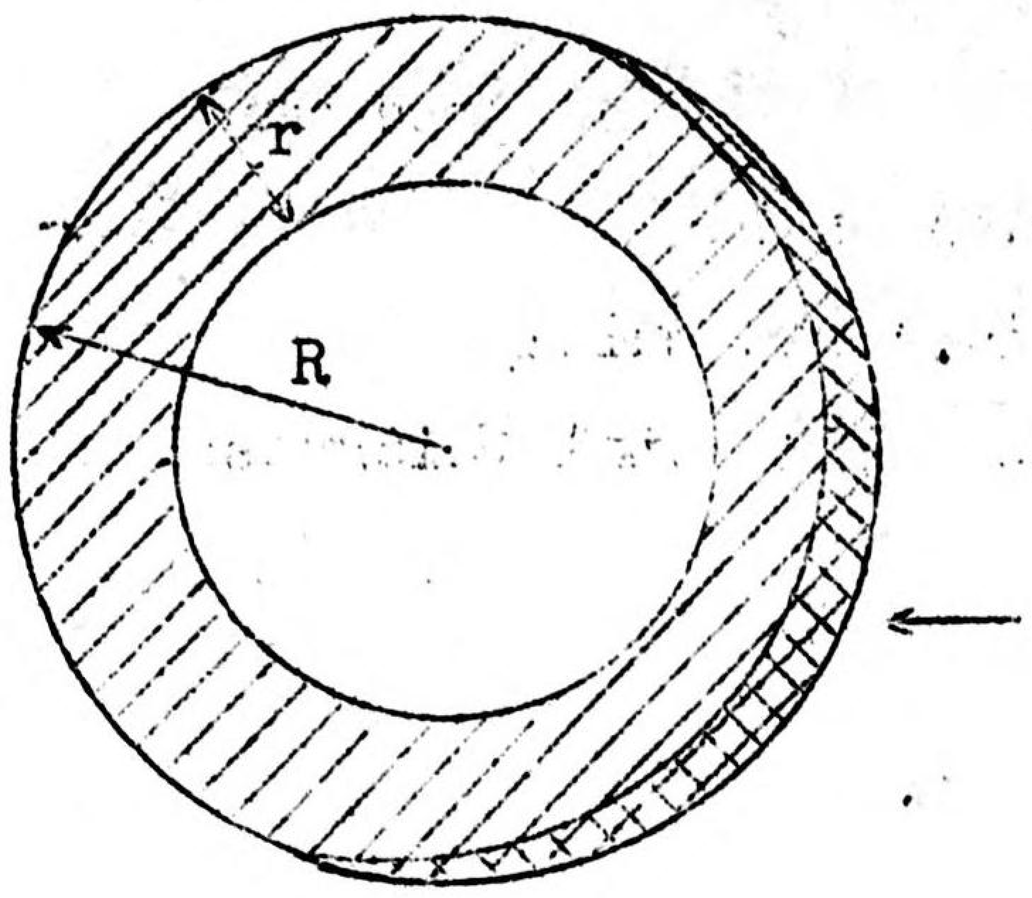

Fig. 4.

be deducted from the vulnerable area. However, this will generally be very small compared to the vulnerable area and will be neglected. If the vulnerable area is A, the assumed uniform bombing density in tons per unit area is D, and the weight of each bomb is W (ton), the probability of at least one hit is

$$p = 1 - e^{-AD/W}. \qquad (3)$$

For equal bombing densities, therefore, A/W is a measure of probability of hitting the vulnerable area of a target. Since $r = \sqrt{W/3t}$, we can say, for GP bombs up to 2000 lb at least, that r is proportional to $W^{1/2}$ for the same thickness t. Hence, on substitution in Eq. 2,

$$A = \frac{2\pi R}{\sqrt{3t}} W^{1/2} - \frac{\pi}{3t} W = C_1 W^{1/2} - C_2 W, \qquad (4)$$

where the C's are composite proportionality factors.

Then

$$A/W = C_1 W^{-1/2} - C_2. \qquad (5)$$

In looking for the maximum of A/W with respect to W we take the derivative, which is

$$\frac{\partial}{\partial W}\left(\frac{A}{W}\right) = -\tfrac{1}{2} C_1 W^{-3/2} < 0. \qquad (6)$$

Thus the efficacy, A/W, increases with decreasing W, and the smallest bomb that will penetrate and detonate within the tank will be the most efficient. This conclusion may require modification when stowage of bombs on planes is considered. For equal stowage efficiency the 100-lb GP bomb is most efficient against tanks of any size that it can penetrate. The tests tended to confirm this general conclusion. The conclusion would be valid even if the vulnerable annulus theory was not entirely correct, provided only that the distance r varied with W^n where $n < 1$.

Since even a 100-lb GP bomb will penetrate 3/4-in. steel plate without breakup if it has a velocity of at least 300 ft/sec,[3/] it appears likely that any GP bomb, 100 lb or larger, if dropped from at least 3000-ft altitude will penetrate.

3/ Data Sheet 2C5* of "Weapon Data, fire, impact, explosion," Division 2, NDRC.

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September 5, 1945
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Project AN-29

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Princeton University
W. Bleakney, Supervisor

AIR ATTACK ON STEEL MILLS

by A. A. Ziegler

Abstract

In a steel plant large enough for coke ovens and steel furnaces to be used as separate targets, the best bombs are the 500-lb GP fuzed 0.025-sec delay for the coke ovens and the 2000-lb GP fuzed 0.025- or 0.1-sec delay for the steel furnaces. If one over-all attack is to be made, the best bomb is the 1000-lb GP fuzed 0.025-sec delay, with the 2000-lb GP fuzed 0.025-sec delay a good second choice.

The principal components of a steel mill in order of their vulnerability to bombing attack, the recommended bomb and fuze delay, and the results to be expected from bombing attack are given in Table I.

Table I. Vulnerability of components of steel mill to bombing attack.

Component	Recommended Bomb	Recommended Fuzing	Results
Coke ovens	500-lb GP or 1000-lb GP	0.025-sec delay	One direct hit will disable one section for 3 to 8 months. This will reduce the quantity of coke and gas available to the blast furnaces. Auxiliary equipment, such as the aspirating plant, coke loading and ramming equipment, and so forth, is also highly vulnerable.
Open-hearth furnaces	2000-lb GP or 1000-lb GP	0.025-sec or 0.1-sec delay	At least 25% of the furnaces must be damaged to affect production seriously. Damaged ovens require several months for repairs. Gantry cranes and other equipment are additional targets.
Blooming mills	2000-lb GP or 1000-lb GP	0.025-sec or 0.1-sec delay	These are frequently a bottleneck of the plant. Small target, but essential to operation and difficult to repair. Smaller bombs could damage controls.
Blast furnaces and related equipment	2000-lb GP	0.025-sec or 0.1-sec delay	Direct hit required. Small target. Stoves, hoists, and charging equipment are also vulnerable to smaller bombs. Long repair or rebuilding time if direct hit is made on furnace.
Conveying equipment and services	500-lb GP or larger		Good secondary objectives within target area. Bridge cranes at ore docks, coke pushers, gantry cranes throughout plant, and so forth, are all essential and vulnerable to direct hits. Services are essential and vulnerable to direct hits or near misses.
Air compressor	2000-lb GP or larger	0.1-sec or 0.025-sec delay	Important, but of very heavy construction. Small target difficult to hit and damage.

1. Introduction

There are very few incidents and very little other information that can be used to verify any recommendations which may be made for attack on steel mills. Such recommendations must be made on the basis of a knowledge of the function and construction of the many components of a steel mill.

There are three principal operations in the production of steel, and the basic piece of equipment for each operation is as follows:

(i) coke ovens, in which coke is produced from coal with various gases as by-products;

(ii) blast furnaces, which are used for the reduction of iron ore to relatively pure iron;

(iii) steel furnaces, in which the iron is alloyed with other materials, principally carbon, to form steel.

After being cast as ingots the steel usually undergoes a fourth process at the mills. The equipment here is

(iv) blooming mills and rolling mills, in which the steel is rolled to the shapes necessary for structural usage (plates, channels, beams, and so forth).

In a modern integrated steelworks all four of these processes are carried out on the site and all processes are carefully integrated for the purpose of producing a continuous flow of finished steels from the raw materials. In such a works no section is independent, each being dependent on a continuous and properly regulated flow of primary products and on the exchange and use of by-product gases in the production of these primary products.

All steel plants, however, are not of this nature. In many cases only one or two of the basic processes are carried out at one plant; the material is then transported to another plant for the remaining processes. This latter arrangement is the one most commonly found in Japan, and it was therefore evident that any attack on the already overburdened Japanese transport system would have a direct effect on steel production. This was particularly true of shipping since the Japanese had coke and blast-furnace facilities on the mainland, the products of which had to be shipped to other mills in the home islands for completion of the steelmaking process.

For either arrangement the basic processes are the same and are attacked in the same manner. To stop the production of steel it is not necessary to destroy an entire steel plant; complete and permanent stoppage of any of the basic processes will achieve the same result. However, because of stocks on hand, the destruction of any process will not be immediately felt.

To appreciate fully the difficulties in bombing a steel mill, the construction and relative importance of each individual component of the plant must be understood.

2. Construction and importance of components of a steel mill

(a) Coke ovens. — The first of the basic processes is the manufacture of coke. Steel cannot be produced without coke for use in the blast furnaces. Therefore destruction of coke-producing facilities directly affects the production of steel. From the point of view of bomb damage, coke ovens may be classified into two types. The older type, which can be repaired after a hit with only the damaged parts needing repair work, and the modern type, which undergoes excessive cracking as a result of cooling and which requires complete relining if cooled for repairs or cooled because of loss of control resulting from bomb damage. This means that the damage done to the older types of ovens is essentially limited to the radius of damage of the bomb, while the damage to the newer types includes the entire oven section.

Most coke ovens, both older and modern types, are built in batteries of four or five sections, each section being about 100 to 125 ft long and made up of some 30 to 40 ovens $3\frac{1}{2}$ ft wide, center to center. The sections are about 50 ft wide, so that the plan area for attack is about $50 \times 120 = 6000$ ft^2. The tops are made of good-quality brickwork about 3 ft thick, and control equipment, loading chutes, and so forth, may mask some of the oven top for bombing attack.

Since a 500-lb GP bomb is the smallest that can be counted on to perforate the top, it is the smallest bomb that can be used. If the enemy is known to have placed any protective cover over the ovens, or if the roof thickness is greater than 3 to $3\frac{1}{2}$ ft, 500-lb SAP or 1000-lb GP bombs should be used. Delay fuzing of 0.025 sec or longer should be used to allow the bomb to penetrate well into the ovens, and to allow for possible slowing up by equipment above the ovens. Deflection of the bombs by such ancillary equipment as chutes above the ovens may cause misses and should be taken into account when determining the area vulnerable to bombing in planning force requirements. These deflected bombs will not damage the ovens themselves, but damage to other equipment may have an appreciable effect on operations.

The extent of the damage is measured by the length of the damaged portion and not, as in the usual case, by a circle of radius equal to the radius of damage. Since the individual ovens extend through the entire width of the section the area damaged is equal to the length damaged times the width of the section.

Such figures as radius of damage and MAE (mean area of effectiveness) are meaningless for a modern-type oven since the important factor is not the amount of damage but the time required for repair: the entire section must be cooled and relined, regardless of the amount of damage. The time spent on repairs is but a small percentage of the total time the oven is out of operation; it is the cooling and reheating which account for most of this time, and these two processes must be carried out regardless of the extent of the damage.

For the older-type ovens the radius of damage will give a measure of the work needed for repair, but here again it is the time out of operation that is important. Most of the time is required for cooling and reheating and this time will not vary greatly with differences in damage provided, of course, that the damage is sufficient to necessitate cooling the ovens before repair. A direct hit by a delay-fuzed 500-lb GP bomb will cause such damage.

Near misses farther than 2 ft from the ovens generally do not cause damage except possibly to the ancillary equipment, which is important. The ovens themselves should be the primary target. If gas-collection pipes are damaged, the sections unaffected may be operated independently and repairs may be made quickly. Coal towers, hoppers, ramming equipment, and so forth can all be damaged, as can the aspirating plant, by-products plant, and so forth. If the aspirating plant or the ramming equipment is knocked out, an entire battery may be put out of operation long enough for cooling to damage the ovens. However, the time depends on such factors as the ingenuity of the operator, the availability of men and materials for temporary repairs, manual handling of coal, and makeshift ramming equipment.

Recommended bombs in the order of preference are: 500-lb GP, 1000-lb GP, 500-lb SAP, and 1000-lb SAP fuzed 0.025-sec delay or longer. A single hit on an oven section with any of these bombs will put that section out of operation for 3 to 8 months, but the rest of the battery will probably continue to operate. All of these bombs are also effective in damaging nearby equipment.

(b) Blast-furnace plant. -- The blast-furnace plant consists of the blast furnace and its ancillary equipment: (i) blast furnace, (ii) charging apparatus and storage and mixing bins, (iii) hot-blast stoves, (iv) blowing plant, (v) gas-cleaning plant, (vi) railway sidings, (vii) calcining kilns, and (viii) ladles and molds.

(i) Blast furnace. A very substantial loss in production can be expected from the destruction of a blast furnace, 12 to 18 months being required for the construction of a new furnace. However, complete destruction of a blast furnace is an unlikely event except in the case of a direct hit by an extremely large bomb. Consider its construction. A modern blast furnace is 80 to 100 ft high, of 15 to 20 ft inside diameter, depending on the required capacity, and stands on a very substantial concrete foundation. The lower 10 or 12 ft of the furnace is known as the hearth and is a receptacle for the molten metal and slag. The bottom of the hearth is usually 8 or 9 ft thick with walls of firebrick about 5 ft thick. The section above the hearth is called the bosh. This is the part of the furnace in which the smelting occurs. The walls of the bosh are of firebrick about 30 in. thick. Steel cooling plates are inserted in this wall to protect the brick from the high temperatures (2800° to 3000°F) maintained in the bosh. These walls, as well as the hearth, are reinforced by a steel jacket. The upper portion of the furnace, some 30 to 50 ft high, is called the stack and has firebrick walls which vary in thickness from 5 ft at the bottom to 1 ft at the top. The stack is externally reinforced by a steel jacket $\frac{1}{2}$ in. thick. All of the steel jackets of the furnace as well as the cooling plates in the bosh are water cooled. Should the water-cooling system cease to function, serious damage to the furnace would result.

The furnace is charged at the top and is fitted with a "double bell and hopper" arrangement which permits charging without loss of gas from the furnace.

A blast furnace is normally in continuous operation for a period of 4 or 5 years. Operations must usually be suspended at the end of this time so that the furnace may be relined and other maintenance work may be performed. The repair period varies from 3 to 6 months, depending upon the extent of the work to be performed. The furnace is so constructed that any part may be removed for repair without disturbing the remaining portions. This arrangement, of course, is quite advantageous in expediting the repair of air-raid damage.

It is obvious from the sturdy construction of a blast furnace that a direct hit by a very large bomb would be necessary to produce substantial damage. Hits on the side of a furnace would almost certainly ricochet because of the small angle of impact. This leaves only the open top of the furnace, a circle 15 to 20 ft in diameter, as a target, and the probabilities of hitting it are small indeed.

A survey of 12 English steel plants attacked by the Germans showed only one direct hit on a blast furnace. The top of the furnace was hit by a 1000-kg bomb and the structural damage was classified as severe. However, repairs were quickly made and only 2 days' production from that furnace was lost.

The obvious conclusion is that a blast furnace itself is not a profitable target. This is particularly true since some of the ancillary equipment is more easily destroyed and its loss can quite effectively shut down a furnace. The use of 2000-lb GP bombs, fuzed 0.025-sec or longer delay, will be effective if hits are obtained.

(ii) Charging apparatus and storage and mixing bins. The materials to be charged into the furnace are delivered by rail from the stock yard over a trestle to the bins near the furnaces. Under the trestle and bins is the "stock house." Here the proper amounts of ore, coke, limestone, and so forth, are mechanically measured out, mixed, and placed in the skips. The skips then carry the "burden" to the tops of the furnaces.

Charging operations in a modern blast furnace cannot be carried out at all satisfactorily without this specialized apparatus. It would probably be possible to keep the furnace in operation without this equipment, but only on a very limited scale. It is the general opinion of experts in the steel industry that a loss equivalent to about 3 months' production of a furnace would occur if that furnace's charging apparatus were destroyed. General-purpose bombs of 500-lb or larger size with delay fuzing should be effective.

(iii) Hot-blast stoves. Hot-blast stoves are essential for blast-furnace operation. They heat the air blast for the furnace, are usually about 20 ft in diameter and 50 ft high, and have brick walls 2 to 3 ft thick. There are usually 4 stoves to a furnace, but only 2 or sometimes 3 are in use at one time. This means that under normal operating conditions there is a large surplus of stove capacity. Further, the stoves are so interconnected that no loss would occur except in the case of the destruction of a large number of stoves. The destruction of 50% of the total number of stoves would cause a loss of pig iron of about 20% for the 6 months required to construct new stoves. It is recommended that 1000-lb or 2000-lb GP bombs, delay fuzed, be used.

(iv) Blowing plant. Blast furnaces cannot operate without the hot air blast. The blowing plant, then, is another vital point in the steelmaking process. It is the normal practice to house all of the blowing apparatus in one building. This is the usual steel-framed single-story type used to house heavy machinery. Stand-by capacity of 10 to 20% of the normal requirement is usually maintained. The blowing machinery itself is extremely large and heavy and probably could not be destroyed except by the very largest bombs. The air pressure maintained by the blowing machines is rather low (2 to 4 lb/in^2), but the volume of air required by the blast furnaces is tremendous -- hence the use of such large machinery. The only unusual feature of the blowing house is the heavy concrete floor (approximately 5 ft thick) necessitated by the machinery. It is not likely that any bomb smaller than the 12000-lb GP would do sufficient damage to delay blast-furnace operations.

(v) Gas-cleaning plant. The effects of destruction of the gas-cleaning plant will vary according to the uses made of the gas. It is the usual practice to use the blast-furnace gas at the coke ovens, soaking pits, reheating furnaces, and stoves and for heating the boilers if the blowing plant is steam operated. In some plants, principally in Germany, the entire blowing plant is gas driven. The gas must be cleaned to be efficiently used for any of the afore-mentioned purposes. The gas-cleaning plant would require 6 months for replacement and if destroyed would result in severe loss of output for this time unless some other supply of gas or source of power were available. It is recommended that 500-lb GP bombs fuzed 0.01-sec delay be used.

(vi) Railway sidings. Railway sidings are essential and can be destroyed relatively easily but are not a good target since they can be repaired quickly.

(vii) Calcining kilns. The kilns are used to improve ores containing high percentages of impurities. However, these ores may be charged directly into the blast furnace, with only a small loss in efficiency. Hence the calcining kilns cannot be considered a profitable target.

(viii) Ladles and molds. Ladles and molds are essential items but usually exist in such numbers that it is improbable that enough of them would be destroyed to affect production.

(c) Steel furnaces. -- The third of the basic processes is the conversion of the iron into steel. This is accomplished in the steel furnaces, three types of which are in common use: open-hearth furnace, electric furnace, and Bessemer converter.

By far the greatest proportion of steel is produced in open-hearth furnaces. The electric furnace is used for steels of particularly high quality. The Bessemer converter is little used since it no longer has any particular advantage over the open hearth and since it produces a steel of inferior quality.

Open-hearth furnaces are usually arranged side by side in a long row in a steel-framed building. Individual furnaces vary in capacity from 10 to 300 tons. It is the general practice, however, to use furnaces of 100- to 150-ton capacity. The approximate size of such a furnace would be 80 by 20 ft, and it would be tapped about every 12 hours.

The furnace hearth rests on a heavy concrete foundation, and the walls of the furnace are of thin steel plate supported by a structural-steel frame. The inside of the furnace walls are lined with about 1 ft of brickwork.

A direct hit by a 500-lb GP bomb would probably destroy or severely damage an open-hearth furnace. However, it requires the destruction of several furnaces to affect production materially. This is due to the fact that normally only about 75% of the furnaces are in operation, the remainder being in some stage of repair. By speeding up work on the furnaces being repaired and by delaying maintenance operations on those in use, it is possible to offset partially the loss of several furnaces. About 3 months would be required to replace a destroyed furnace. The number of open-hearth furnaces found in a steel mill varies from about 5 for a very small plant to about 40 for a large plant.

The accessory equipment to the furnaces includes the charging floor and the charging machines. The destruction of the raised charging floor would put the furnaces out of operation for about 1 month, but it is highly improbable that complete destruction of the floor could be effected and, further, any damaged portion could be temporarily repaired very quickly. The charging machines are essential, but it is the usual practice to have two or more of these machines in an open-hearth building -- any one of which can be used to service all of the furnaces in that building. It is unlikely that all of the charging machines would be destroyed.

In addition to the furnaces themselves another vital and vulnerable component of the building is the casting cranes. When a furnace is tapped, the molten steel runs into a large ladle, usually of 150-ton capacity. This ladle is then carried by the casting crane to the ingot molds where the steel is cast as ingots. These cranes are of specialized construction and could not be replaced and installed in less than 4 months. Much more vulnerable than the cranes themselves, however, are the columns and girders of the building frame upon which the cranes are supported. Hits on the building stand a good chance of distorting or damaging the structural members so that the cranes will not be able to operate. Re-aligning and "truing up" the building frame is a tedious job which on the average would require about 4 months. Because of the unusual capacity of the cranes the building frame must be quite substantial. Although 1000-lb GP bombs could be used if necessary, 2000-lb GP bombs or larger are recommended. Best results will probably be obtained with 0.025-sec or longer delay fuzing.

The open-hearth building is recommended as the second best point of attack (coke ovens are the best point of attack) in a steel plant. These buildings are easily recognized from the air and present a much larger target than most of the other buildings of a steel plant. In addition, any hit on the building is almost certain to cause important damage.

A survey of the 12 steel plants in England attacked by the Germans showed only one hit on a furnace building. In this case the bomb was a parachute mine and the damage resulted in a loss of two weeks' production. Since the roof of the building was destroyed and blackouts had to be observed, part of the loss occurred because night operations were suspended for three weeks while a new roof was installed.

(d) Blooming mills and rolling mills. — The remaining process in the production of finished steel is carried out in two principal stages, first at the blooming mills and second at the rolling mills (sometimes called finishing mills). Bombing of blooming mills and rolling mills can cause a reduction in the production of finished steel. However, because of the duplication of facilities, it is unlikely that more than a slowing down of production can be achieved. The principal bottleneck occurs at the blooming mills through which all the ingots must pass for rough shaping before being distributed to the various rolling mills.

The important components of the blooming mills and rolling mills are rolls, motors, soaking pits, reheating furnace, cranes, and building structure.

The rolls are made of cast steel, are difficult to destroy, and exist in such large numbers that they can easily be replaced. More vulnerable are the frames or stands which support the rolls. These would take 1 to 2 months for replacement, but since all except the very smallest mills have several stands of rolls which can perform the same function, destruction of one would merely decrease production, not stop it. Each stand of rolls is operated by its own electric motor. The motors are usually installed below ground level and are thus well protected from all but direct hits.

Soaking pits and reheating furnaces are necessary for the proper heating of the steel for rolling. They are rather substantially constructed of concrete, steel, and brick. The fact that there are usually several of each makes it difficult to do more than slow down production.

Cranes and building structure are vulnerable to almost the same extent as they are in the open-hearth building. The principal differences are that the rolling-mill cranes are much lighter and exist in greater numbers than those of the open-hearth building. Also the building structure is lighter because of the smaller crane loads.

Table II shows the results of hits made on rolling mills in German raids on English steel mills.

Table II. Results of hits on rolling mills in German raids on English steel mills.

Bomb	Number of Bombs	Location of Hit	Loss of Production
Para-mine	1	Mill building*	1 yr
250-kg	1	Soaking pit	None
1000-kg	1	Soaking pit	8 wk
50-kg	1	Rolls	None
Para-mine	1	Rolls	None

*This was an old wall-bearing building and the entire structure collapsed..

3. Conclusions

The most profitable point of attack in a steel plant is the coke ovens provided sufficient other outside sources of coke are not available. In order of preference the best bombs are: 500-lb GP, 1000-lb GP, 500-lb SAP, and 1000-lb SAP, fuzed 0.025-sec delay or longer.

The second best point of attack is the open-hearth buildings. The best bombs in order of preference are 2000-lb GP and 1000-lb GP, fuzed 0.025- or 0.1-sec delay. Bombs larger than 2000-lb GP may be profitably used against this target.

Blast furnaces and their auxiliary equipment present small target areas, but can be seriously damaged by 2000-lb GP bombs fuzed 0.025-sec delay if hits are obtained.

There are other targets, such as the water system and gas mains, destruction of which can cause severe damage and long delays in production. However, since they present such small targets, are so difficult to hit, and probably could not even be located from an attacking aircraft, it is not considered worthwhile to select them as aiming points. Damage to such equipment is best caused by delay-fuzed bombs, so that misses from bombing other parts of the steel plant may cause loss of production by damaging utilities.

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CONTENTS