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UNITED STATES OF AMERICA

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TECHNICAL DIVISION

PICATINNY ARSENAL

BLAST EFFECTS OF BOMB EXPLOSIVES

LECTURE BY:

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9 APRIL, 1948

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ORDNANCE DEPARTMENT

U. S. ARMY

BLAST EFFECTS OF BOMB EXPLOSIVES

The importance of bombing as a military operation during the recent conflict lead naturally to a considerable expenditure of energy and effort aimed toward the development of improved bomb filler. In a previous lecture on explosives used during World War II, those employed for various purposes were reviewed briefly with an explanation for their adoption for the particular use. It would be interesting to see what a wealth of technical development lay hidden behind the two short paragraphs of the previous coverage. To this end, a short description of the effects of bomb explosions, gratefully purloined from an excellent BRL report on the subject, is presented (BRL No. 477).

Action of Detonating Bomb on Surrounding Medium

Description of the detonation. When a bomb detonates, its explosive charge is converted with extreme rapidity into a gas of very high pressure and temperature. The exact pressure and temperature vary with the kind of explosive contained in the bomb; the order of magnitude is 100,000 atmospheres (700 tons per sq in.) for the pressure and 3,000 centigrade (5500 F.) for the temperature. The detonation is initiated by the operation of a fuze in the nose or tail of the bomb, and it propagates with a velocity between 15,000 and 28,000 ft per sec depending on the type of explosive. Thus, the time required for the detonation of the charge of a 500-lb bomb is approximately 0.0001 sec. [illegible] this time, a bomb falling at 800 ft/sec travels about 1 inch.

Under the pressure of the detonating gases, the metal casing of a bomb expands very rapidly like a balloon to approximately 1-1/2 times its original diameter (Fig. 1).

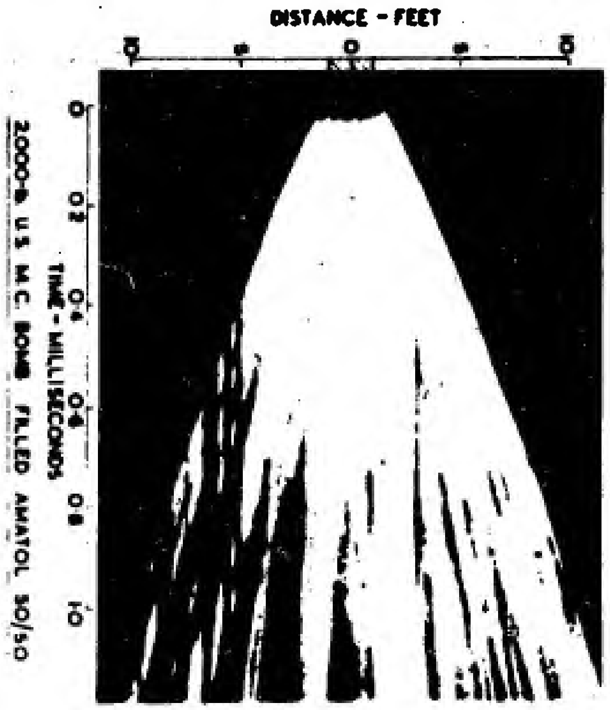

Fig. 1

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It then breaks into fragments. The strength of the metal casing does not constitute a serious obstacle to its expansion; it is the inertia of the casing and of the gases themselves that limits the rapidity of expansion. The velocity of expansion may be as high as 10,000 to 15,000 ft/sec for bare charges or for charges whose cases are extremely thin, but it is from 5 to 8 times lower for heavy-walled armor-piercing bombs. A considerable fraction of the energy released by the detonation is spent in the process of accelerating the casing during its expansion. This fraction is directly related to the weight of the casing itself or, more accurately, to the weight per unit area for each part of the bomb. For a GP bomb having a casing and charge of approximately equal weight, the fraction of energy expended in this way is close to 50%.

Flash photographs give a pictorial description of the course of detonation of cylindrical bombs. Such a description is shown in Fig. 2.

FIG. 4.1 PROGRESS OF DETONATION AND OF EXPANSION AND BREAKING UP OF THE CASING ALONG A CYLINDRICAL BOMB. (DETONATION STARTED FROM BELOW).

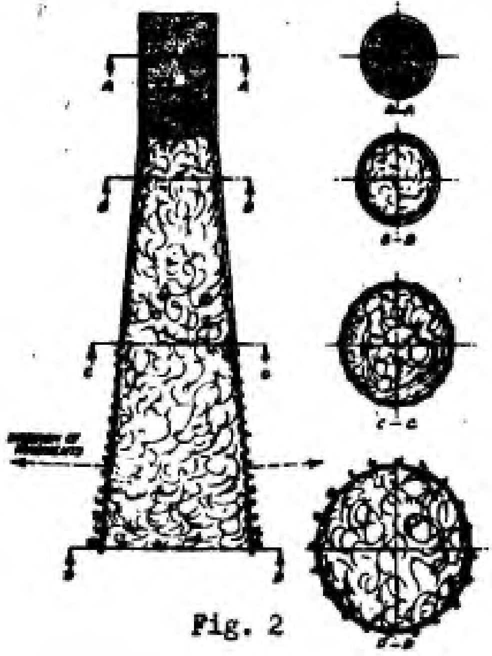


Fig. 2

Here the detonation is assumed to have been initiated from below and has not yet reached the upper part. The middle part is expanding; the lower part, which has detonated first, has expanded farthest, so that its casing is already broken into fragments which are flying outwards.

Detonation in Air

The expanding products of a bomb's detonation sweep out and compress the surrounding air and throw that compressed body of air against adjacent layers of air. In this way a belt is formed within which the air has high pressure and high outward velocity. This belt is limited by an extremely sharp front (less than one thousandth of an inch) called the "shock front" in which the pressure rises abruptly.

The shock front propagates with a velocity which is initially much higher than that of sound (3,000 ft/sec at 60 ft from a 4,000-lb LC bomb, where the pressure jump is 100 psi) and, after a distance, decreases rapidly towards sound velocity (about 1,100 ft/sec) as the pressure jump also becomes smaller. This loss in velocity is generally much more rapid than the slowing down of the casing fragments, so the shock front lags behind the movement of the fragments.

The compression of the surrounding air absorbs a considerable fraction of the energy of the detonation. Most of this energy is transferred to the air when the amount of air compressed by the detonation attains a weight comparable with that of the detonated charge, that is, after the expansion has attained more than five times the original diameter of the charge. By this time, however, the fragments of the casing, flying along divergent paths, have become separated, and most of the front of the detonation products consists of gases. Therefore, it is the gases that supply most of the energy transferred to the air, and this occurs only after the fragments have taken up their share of the initial energy. Thus, the effect of a 500-lb GP bomb on the surrounding air is roughly comparable in intensity to that of a 150-lb bare charge, for the casing of such a bomb absorbs about 40% of the energy of its 260-lb charge. A high charge/weight ratio increases the effect of the detonation on the air in a twofold manner; it will increase the weight of charge included in a bomb of given weight; and it will reduce the fraction of energy given to the fragments. (Figs. 3 and 4)

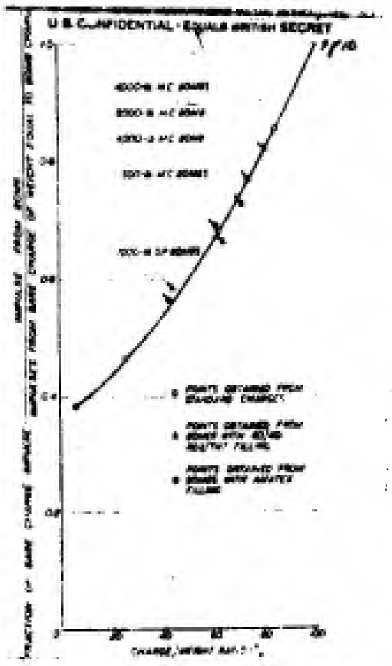


Fig. 3

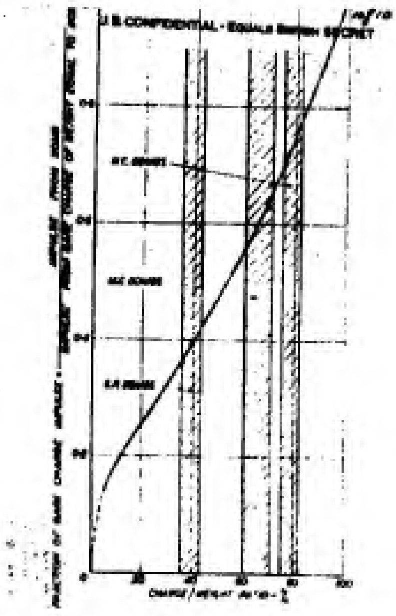


Fig. 4

The air and detonation gases moving outward as a strong wind behind the shock front are prevented by their own inertia from slowing down quickly enough as the pressure of the core of the gases subsides. Thus a rarefaction is ultimately formed where the bomb had detonated; this propagates outward too, trailing the shock front. After the shock passes, both wind and pressure excess decrease until they reverse in sign, the wind blowing back toward the bomb and the pressure becoming subatmospheric. Later, the wind decreases to zero and the pressure becomes normal. Any light object, such as a leaf, that is struck by the shock wave is rapidly accelerated away from the position of the bomb and then blown back, almost to its original position. The shock front, the high pressure behind it and the following rarefaction form a complete wave to which the terms "blast" and "shock wave" are usually applied. (Fig. 5)

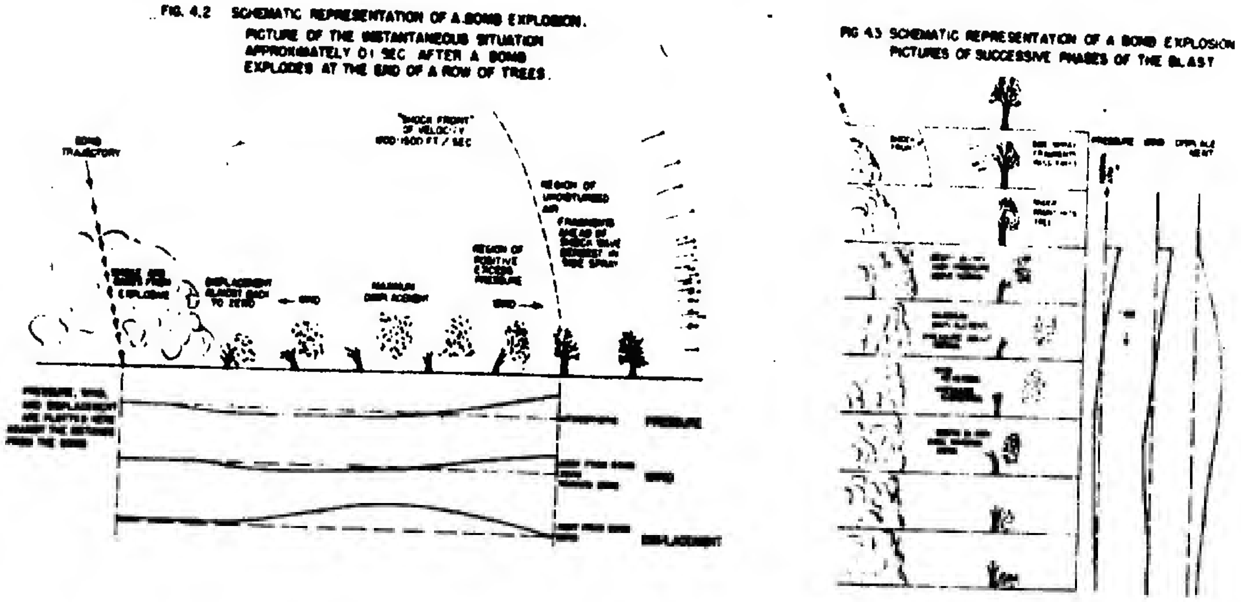


FIG. 4.2 SCHEMATIC REPRESENTATION OF A BOMB EXPLOSION. PICTURE OF THE INSTANTANEOUS SITUATION APPROXIMATELY 0.1 SEC AFTER A BOMB EXPLODES AT THE END OF A ROW OF TREES.

FIG 4.3 SCHEMATIC REPRESENTATION OF A BOMB EXPLOSION PICTURES OF SUCCESSIVE PHASES OF THE BLAST

RESTRICTED

Fig. 5

The time of duration of the positive excess pressure varies from some 0.04 sec at 400 ft from the 4,000-lb LC bomb to about 0.006 sec at 50 ft from the 100-lb GP bomb. The region of negative pressure lasts some four times as long, but the pressure defect is normally much less than the pressure jump at the shock front. (Figs. 6 and 7)

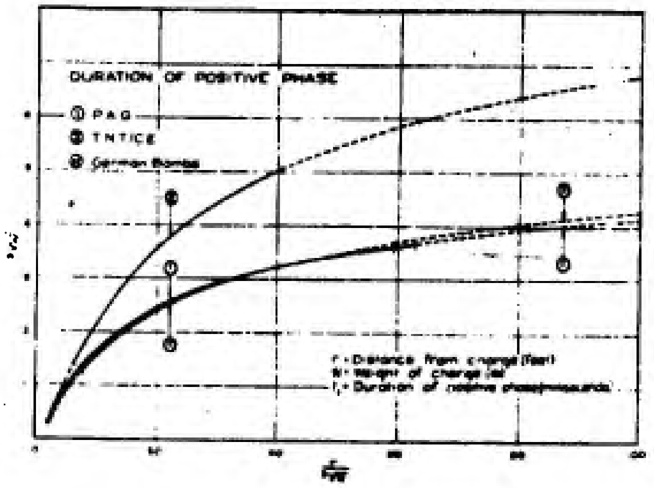


Fig. 6

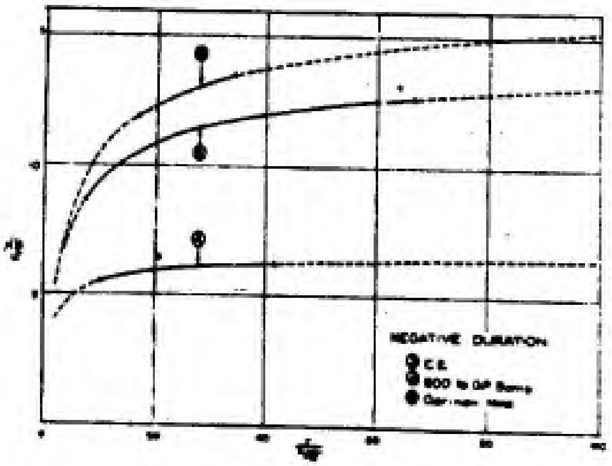


Fig. 7

The wall of a building hit by such a blast wave is first pushed inward by the positive pressure phase and then sucked outward by the negative phase. Whether the wall falls away from or toward the bomb depends on accidental circumstances (such as the ratio of the natural period of the wall to the duration of the positive phase of the blast).

Peak Pressure and Impulse. The physical characteristics of the shock wave around a bomb are usually described by giving the peak pressure and impulse (more properly the impulse in the positive phase of the wave) at various distances.

The peak pressure is the pressure jump at the shockfront, the highest pressure in the shock wave minus the normal atmospheric pressure.

The impulse is the area under the excess pressure-time curve for the duration of the positive phase. This is approximately half the peak pressure multiplied by the duration of the positive phase (Fig. 8).

Typical Pressure - Time Record
for the Blast from a Bomb

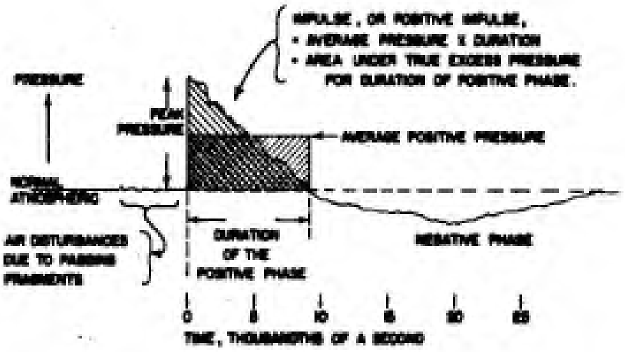


Fig. 8

The peak pressure decreases with distance R from the bomb approximately as $1/R^{3/2}$ to $1/R^2$*.

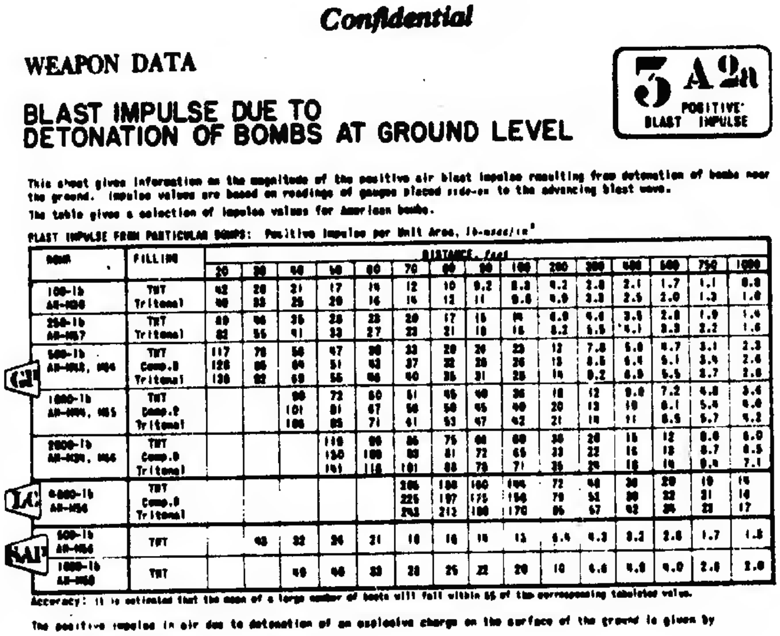
The impulse decreases with distance approximately as 1/R.

The positive phase duration increases approximately as $\sqrt{R}$ to R*.

The peak pressure (at constant distance) varies as the charge weight to the one-half to two-thirds power. The impulse (at constant distance) varies as the charge weight to the two-thirds power.

The values of peak pressures and impulses for various bombs apparently do not vary for different directions and do not depend on the velocity of fall of the bomb at the time of detonation.

*At low pressures (1 lb per sq inch) the decay of pressure is more nearly $1/R^{3/2}$; at pressures of 10 to 100 psi, the decay is more like $1/R^2$. Correspondingly, the increase of positive phase duration is $\sqrt{R}$ at 1 psi. and R at high pressures.



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WEAPON DATA

BLAST IMPULSE DUE TO DETONATION OF BOMBS AT GROUND LEVEL

5 A2a POSITIVE BLAST IMPULSE

This sheet gives information on the magnitude of the positive air blast impulse resulting from detonation of bombs near the ground. Impulse values are based on readings of gauges placed side-on to the advancing blast wave.

The table gives a selection of impulse values for American bombs.

BLAST IMPULSE FROM PARTICULAR BOMBS: Positive Impulse per Unit Area, lb-msec/in²

	BOMB	FILLING	DISTANCE, feet														
			20	30	40	50	60	70	80	90	100	200	300	400	500	750	1000
GP	100-lb AN-M30	TNT	42	28	21	17	14	12	10	9.2	8.3	4.2	2.8	2.1	1.7	1.1	0.8
		Tritonal	48	33	25	20	16	14	12	11	9.6	4.9	3.3	2.5	2.0	1.3	1.0
	250-lb AN-M57	TNT	69	46	35	28	23	20	17	15	14	6.9	4.6	3.5	2.8	1.9	1.4
		Tritonal	82	55	41	33	27	23	21	18	16	8.2	5.5	4.1	3.3	2.2	1.6
	500-lb AN-M43, M64	TNT	117	78	58	47	39	33	29	26	23	12	7.8	5.8	4.7	3.1	2.3
		Comp.B	128	85	64	51	43	37	32	28	26	13	8.5	6.4	5.1	3.4	2.6
		Tritonal	138	92	69	56	46	40	35	31	28	14	9.2	6.9	5.5	3.7	2.8
	1000-lb AN-M44, M65	TNT			90	72	60	51	45	40	36	18	12	9.0	7.2	4.8	3.6
		Comp.B			101	81	67	58	50	45	40	20	13	10	8.1	5.4	4.0
		Tritonal			106	85	71	61	53	47	42	21	14	11	8.5	5.7	4.2
	2000-lb AN-M34, M66	TNT				118	99	85	75	66	60	30	20	15	12	8.0	6.0
		Comp.B				130	108	93	81	72	65	33	22	16	13	8.7	6.5
		Tritonal				141	118	101	88	79	71	35	24	18	14	9.4	7.1
LC	4000-lb AN-M56	TNT						206	180	160	144	72	48	36	29	19	14
		Comp.B						225	197	175	158	79	51	39	32	21	16
		Tritonal						243	212	189	170	85	57	43	34	23	17
SAP	500-lb AN-M58	TNT		43	32	26	21	18	16	14	13	6.4	4.3	3.2	2.6	1.7	1.3
	1000-lb AN-M59	TNT			49	40	33	28	25	22	20	10	6.6	4.9	4.0	2.6	2.0

Accuracy: It is estimated that the mean of a large number of tests will fall within 5% of the corresponding tabulated value.

The positive impulse in air due to detonation of an explosive charge on the surface of the ground is given by

Fig. 9

Due to the reflection of the blast, the instantaneous pressure against a surface facing the point of detonation is actually two or more times* greater than the "hydrostatic pressure" (the pressure on a wall side-on to the blast which is that considered in Fig. 10,

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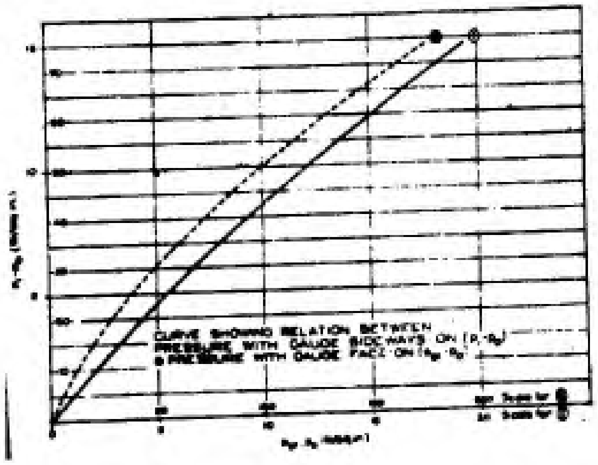

Fig. 10

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*The exact ratio is 2(102.9⁄ 4P)/(102.9 ⁄ P) where P is the hydrostatic pressure in psi.

and which is that normally referred to.) There is a corresponding effect for the impulse.

The peak pressure gives a measure of the maximum force exerted against a structure by the blast (pressure times area = force). The impulse gives a measure of the force multiplied by the duration, which, for an unsupported structure, is proportional to the velocity given to the structure. This is important, for example, in connection with the demolition of brick walls. A blast cannot quickly propagate around anything as large as a wall, therefore, it keeps on deforming it away from the bomb until the positive pressure has subsided. Because of the great inertia of the wall, however, this deformation seldom attains the point of collapse before the positive pressure has subsided. After such time the inertia tends to continue the acquired motion of the wall despite its rigidity. The eventual attainment of a deformation leading to collapse will depend on the velocity acquired by the wall under the impact of the blast.

In general, one may say that in order to demolish any structure, two criteria must be satisfied; the peak pressure must exceed a certain minimum value, and the impulse must exceed a certain minimum value. The values of peak pressure and impulse necessary for demolition depend on the type of structure. The relative values also depend greatly on the type of structure. Window glass, for example, requires a moderately high peak pressure (about 1.5 psi **) but a very low impulse (perhaps 1 lb millisec per sq in.). The positive pressure does not have to last long to cause facture, and the blast from almost any charge that causes a sufficiently high peak pressure will necessarily have sufficient impulse. On the other hand, a brick wall withstands but little higher peak pressure (3-4 psi), but for demolition this pressure must last quite long (that is, the impulse must exceed about 100 lb millisec per sq in.). For most bombs, therefore, if the impulse is sufficient to demolish the wall, there is generally sufficient peak pressure.

This explains the somewhat confusing use of two criteria. In general, both criteria must be satisfied to cause damage. For some targets, however, one of the two criteria is so low that one need only consider the other as that which must be fulfilled to cause damage. In general, structures which, in comparison to the area they present to the shock front, are strong and light in weight, require high peak pressure but no great impulse for demolition. Heavy, but relatively weak structures require large impulse but not very high peak pressure to cause demolition.

** The required pressure depends greatly on the size and thickness of the glass panes, and on the strength of their support. (Occasionally a small fraction of 1 psi may be sufficient to shatter windows.)

Finally, it should be noticed that when the blast hits a narrow object and quickly propagates behind it, the duration of action of the positive blast pressure may be considerably shorter than the duration of the positive phase. The impulse imparted to the object is then simply the product of the peak blast pressure and of its actual duration of action and thus is not correlated with the duration of the positive phase. Under these circumstances the impulse criterion does not come into consideration at all, but the peak pressure determines the impulse imparted to the object.

To give some examples, it is estimated that 500 psi is required to blow out a steel column of ordinary construction, but irreparable damage may be produced by as low as 16 psi for a relatively weak column hit facing to the web up to 150 psi for a strong column hit in line with the web. For comparable destruction concrete columns require pressures about three times higher than steel columns. Furthermore, they do not present any comparatively sensitive face such as a steel column offers facing to the web.

Human beings have about a 50:50 chance of surviving 500 psi, but will probably be severely injured at 70-100 psi. Exposed eardrums will be ruptured 50% of the time at 15 psi. However, a standing man will be blown away at about 10 f/s velocity by a shock of 25 psi peak pressure.

Obstacles fairly large in size, such as walls ten feet high with no opening or with only small openings, offer considerable protection from blast. However, a small cavity such as a foxhole offers practically no protection. The intensity of a blast propagating along a straight tunnel, a corridor, a trench, or even a street, decreases with distance much more slowly than in the open. However, a simple right-angle bend in a tunnel reduces the pressure about 50%. A system of four such bends reduces it to about 15%.

Since buildings with load-bearing brick walls constitute most of the housing districts of England and continental Europe, the "impulse criterion" has had wide application. The "vulnerable radius of demolition" for bombs detonating on the ground or on a roof within a district of houses having 15 inch load-bearing brick walls (current German construction) is taken to be that distance at which the blast impulse has dropped to 110 lb millisec per sq in. The radius, so defined, is the radius of a circle of the same area as the average area around the bomb within which complete demolition will occur. The analogous "vulnerable radius of visible damage" (as detected by aerial observation) corresponds to 50 lb millisec per sq in.

The blast impulse is also the appropriate criterion for determining the effect on light but relatively poorly supported panels and partitions. A wood panel 1 inch thick, facing a blast of impulse 10 lb millisec per sq in., will be blown away with an initial velocity of 30 f/s unless the attachment to the walls, floor and ceiling is secure.

Effects of Confinement. The presence of obstacles that prevent the propagation of blast in some directions may increase the effect of blast in other directions. Little quantitative information is now available on such effects of confinement of the detonation, so that publication of data is not feasible.

In general, however, one may consider two types of effects of confinement:

1. As mentioned above, a blast propagating along a tunnel, a corridor, a trench, and, in the case of a large bomb, even along a street, is effectively confined, so that its intensity decreases much more slowly than in the open. The reflection by the side walls forms a single unit with the blast propagating away directly from the point of detonation. The rate of decrease of the blast intensity depends on the nature of the side walls and cannot be easily estimated.

2. When a small bomb detonates inside a room, demolition of the walls will probably occur even if the distance to the nearest wall exceeds considerably the "vulnerable radius of demolition" as defined above. This is due to a variety of effects, among which is the "multiple punch" effect created by the blasts hitting on a wall in quick succession after having been reflected by other walls. It is estimated that the "vulnerable radius of demolition" is increased for bombs bursting inside brick houses of German construction, so that it corresponds to an impulse of about 65 instead of 110 lb millisec per sq in. It should be noted that even an object readily demolished by the blast, light roof for instance, produces considerable reflection.

Comparative Effects of Various High Explosives. The relative efficiencies of various explosives are presented in Table I (at the back of this report) for several miscellaneous compositions, and in Table II for the blast charges of the most extensive usage. It is apparent from perusal of these tables that the explosives of practical interest may be arranged in the following order of decreasing blast power:

Torpex
Minol
Tritonal
Comp B
TNT
Amatol

Vulnerable Areas and Radii. Aerial reconnaissance of the damage done by large bombs in typical German residential districts has determined the average area of demolition wrought by various types of bomb. The largest bombs are normally used with instantaneous fuzing, so as to burst on the ground surface or on roof tops. The intent is to demolish houses "from the outside" and to produce a wide area of damage by taking advantage of the long range effects of unconfined blast. Under these conditions it appears that the radius of a circle of area equal to the average demolition area is the distance from the bomb at which the blast impulse measures about 110 lb millisec per sq in. Because of this, one may define arbitrarily as "vulnerable area of demolition" for each bomb the area of a circle having for radius ("vulnerable radius of demolition") the distance from the bomb at which the impulse measures 110 lb millisec per sq in. This vulnerable area can then be taken as an index of the blasting efficiency of the particular bomb with reference to detonation on impact in German residential districts. This same area may finally be used to compare the blasting efficiency of all HE bombs, even though most types of HE bombs are not actually used or designed for the attack of German residential districts by unconfined blast.

The "vulnerable area of visible damage" and the corresponding "vulnerable radius of visible damage", taken as the distance at which the impulse measures 50 lb millisec per sq in., have the same base, significance and use as the vulnerable area and radius of demolition.

Medium size and small HE bombs are used to advantage with delay fuzing with the intent of demolishing houses "from within", thus relying on the short range enhanced effect of confined blast. Considerations analogous to those presented for the largest bombs lead to the definition of a "vulnerable area of demolition" and of a "vulnerable radius of demolition" with reference to bombs detonating within houses of typical German residential districts. This radius may be taken as the distance at which the impulse measures about 65 lb millisec per sq in. However, the demolition effect of a bomb detonating inside a house generally does not extend beyond the limits of the house itself. Hence the theoretically defined "vulnerable area of demolition" serves as an estimate of the area that can be demolished only when the corresponding radius is much smaller than the dimensions of a house. This consideration sets an upper limit to the size of bombs that are effectively employed to demolish a given type of building "from within".

The foregoing description indicates, to a limited extend, the complexity of the blast process, which, at best, is just that —— quite complex. As mentioned previously, blast is propagated through air, or other media, in the form of a pressure wave which may be considered qualitatively as a glorified sound wave; i.e., while a sound wave is a wave of infinitesimal amplitude (pressure differential) a blast, or shock, wave is one of finite and quite considerable amplitude. As in the case of other waves, those of shock are subject to certain laws, but due to their finite amplitudes, differences from the behavior of normal waves may be expected. At small angles of incidence (i.e., the angle between the surface and wave front) shock waves are reflected normally, but not with equal angles of incidence and reflection as in the case of sound or light waves. The incident shock wave makes a larger angle with the reflecting surface than the reflected wave and the pressure behind the reflected shock front rises to over twice that behind the incident front at small angles of incidence and close to a critical angle to over three times the latter. Such reflection gives rise to an enhanced pressure wave at ground level and to a double pressure peak above the ground. The two cases free air (above) and above ground burst (below) are illustrated in Fig. 11.

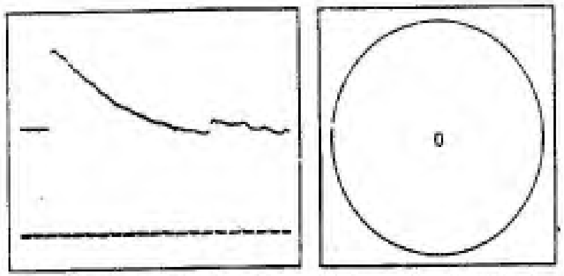

FIG. 1 TYPICAL PRESSURE-TIME CURVE IN ABSENCE OF GROUND REFLECTION

FIG. 2 SPREAD OF SHOCK WAVE FROM FREE-AIR EXPLOSION

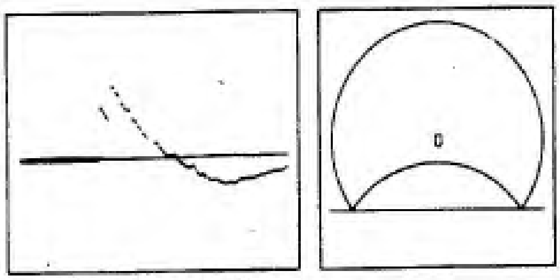

FIG. 3 PRESSURE-TIME CURVE WHEN THERE IS A GROUND REFLECTION

FIG. 4 GEOMETRY OF REGULAR REFLECTION

Fig. 11

along with the type pressure time-curve concerned. When the angle of incidence exceeds the critical value, dependent on the strength of the shock and decreasing with it (90° for very weak, 40° for very strong shocks), the reflected wave is no longer normal, but consists of two parts, one reflected at an angle smaller than that of incidence and the other propogated along the surface. This system of three shocks also involves a density discontinuity, or slip stream, all of which are centered about one point called the triple point. In such a case, termed Mach reflection, the reflected shock is not formed at the reflecting surface, but at the tip of a high pressure region called the Mach region, the front of which is called the "stem". The stem is, of course, the third shock and the pressure behind it is approximately twice that of the incident shock. The triple point, or top of the high pressure stem, travels away from the surface along a path that is straight for plane incident shocks, but, as shown in the slide, is curved for spherical shocks. This type of reflection accounts for the focusing action of the shaped charge which greatly increases the pressures exerted facing the cavity.

C	Charge	D_0	Horizontal distance from charge to point where M leaves ground
I	Incident shock wave	h_c	Charge height
R	Ground reflection	α	Angle made by incident shock and the horizontal at the point of reflection
Stem	Mach shock, front of Mach region	α_{ext}	Value of α at D_0
S	Slipstream	ϕ	Angle made by horizontal and the chord of ℓ-ℓ from D_0 to any point on ℓ-ℓ
M	Triple point		
ℓ-ℓ	Locus of triple point		
D	General horizontal coordinate		

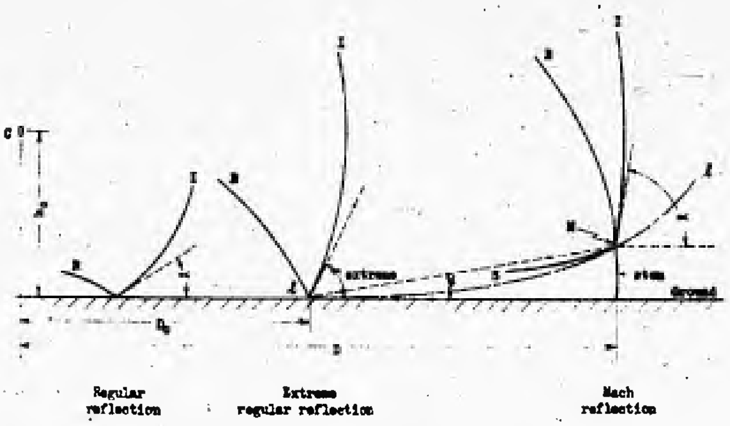

Fig. 37. Successive shock configurations from 1-lb charge.

OSRD 4943

Fig. 12

SUMMARY

Cavity charges, also known as shaped or hollow charges, make use of a phenomenon that underlies one of the more spectacular ordnance developments of this war. This phenomenon is an outgrowth of experimentation conducted in the 18th and 19th centuries, which demonstrated the effect of shaping an explosive charge. This remained little more than a laboratory curiosity until recent years when the discovery that a metal liner, in the charge cavity, greatly enhanced its effectiveness.

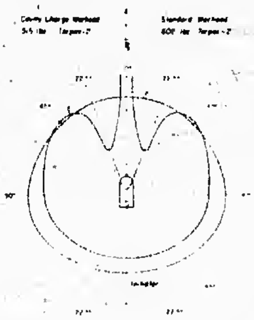

Fig. 1.

Sketch comparing approximate relative peak-pressure distributions of two torpedo warheads, one with a cavity charge and one without. Sketch is based on limited experimental data.

Fig. 13

The discovery, combined with other new ordnance equipment, gives great armor-piercing qualities to relatively light projectiles. For example, by using a charge shaped to produce this phenomenon, a pair of infantrymen now can be given fire power sufficient to stop and destroy a heavy tank.

The metal-lined cavity permits the charge to produce a powerful penetrating metallic jet which pierces the target. Very little target material is lost by this action; practically all is merely pushed aside. This does not

It also complicates the air blast picture by producing, due to reflection of shock waves from the ground, a region of higher than normal blast pressure when a bomb is detonated above the ground. This is accomplished as indicated in the slide

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WEAPON DATA

MACH REFLECTION

3 A7
MACH REFLECTION

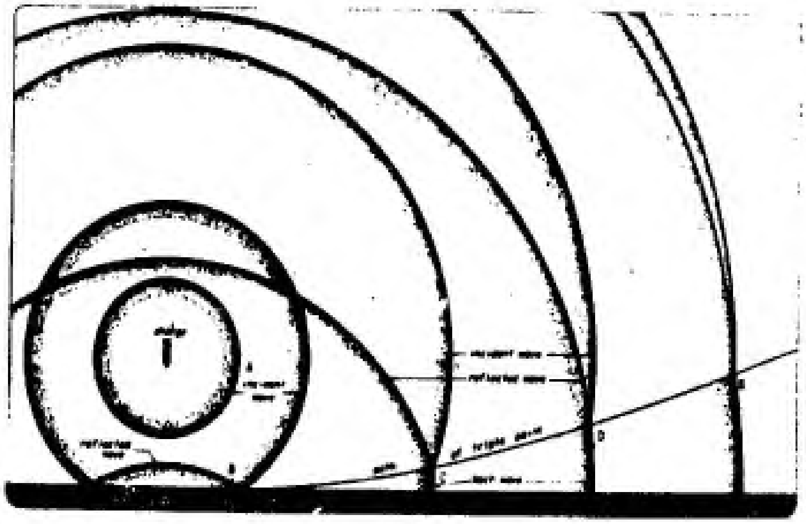
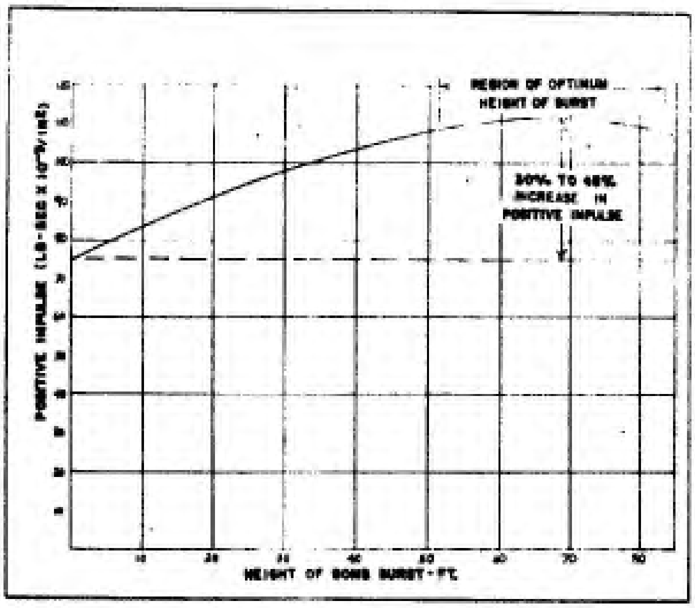


Fig. 14

and results in the high pressure region extending from the ground to somewhat above the triple point whose path is also indicated in the slide. Thus it is possible to maximize the blast exerted at a given point by causing the bomb to explode a certain distance above the ground.



ESTIMATED POSITIVE IMPULSE AS A FUNCTION
OF HEIGHT OF BURST OF A 4000-LB. L.C. BOMB.

Fig. 15

To best accomplish demolition of a structure, it appears desirable to have the bomb explode at such a height that the triple point will pass through the structure at about its center of gravity. Pressure and impulse appear to be maximized just above and below the triple point respectively, so that this point is the approximate location of maximum blast.

The interaction between a bomb and its surroundings may seem quite complicated, but in spite of this, it is necessary to construct a reasonable and workable theory as to the causes of some of the effects noted in order to permit efficient work on the development of improved bomb explosives. A good starting point for such an air-blast theory is found in the answer to the question "From whence comes the energy required to cause the observed demolition effects?" Certainly, it is obvious, the explosive itself must supply the energy through chemical reaction, but the explosive itself represents in almost all cases, only a part of the total of reactants. It has been shown that the oxygen of the atmosphere takes part in the blast reaction to a significant extent; the only exception to this being in the case where the explosive contains within itself sufficient oxygen for complete combustion, which is not the case for any standard bomb filler. N.G., however, is completely oxygen balanced, + 3.5%, and when detonated in nitrogen, oxygen, or air has the same blast effects. Tetryl and TNT, on the other hand, show decreases in efficiency when the surrounding atmosphere is changed from oxygen to air to nitrogen. It has also been shown that the amount of oxygen effectively utilized in this way, i.e., in afterburning, is never as much as the amount required for complete combustion.

Thus the material reacting to produce energy which can be utilized in the blast process is the explosive plus an indeterminate amount of oxygen from the air. A second pertinent question would be "When and where is the energy produced?" First, part of it can be and is produced during the detonation proper and within approximately the volume originally occupied by the charge. In addition, however, after the detonation proper has occurred, and during the expansion stage, additional energy can be produced over a volume considerably larger than the original one. This additional energy is, of course, produced by chemical reaction and can be derived from the following sources:

a. Further reaction of any incompletely reacted portions of the explosive charge.

b. Any change, by reaction, of the composition of the explosion products, due to changes in temperature and pressure conditions, or to differences in the rates at which certain components interact with others, and

c. Further oxidation of the explosion products by atmospheric oxygen.

The amounts of energy released in any of these processes are governed by the chemical equation involved, and the pressure, temperature and concentration conditions at the time and point in question.

It is common knowledge that, in general, the brisance or shattering ability of a charge is proportional to its rate of detonation. This is so because shattering ability at the charge surface, i.e., fragmentation, is the military definition of brisance and only energy evolved during detonation (within the original charge volume) is effective in this case. Certainly, energy produced by reaction after the case has fragmented cannot be effective. The detonation energy is proportional to the rate, and this establishes the proportionallity between brisance and rate. There is a rather widely held popular belief that blast is also roughly proportional to rate or brisance, and while this is true where only detonation energy is involved, the relation breaks down badly in cases where the after-detonation-reactions assume importance. Comparison of the air-blast efficiencies and rates tabulated in Table II (at the rear) shows the lack of correlation.

Consider, for example, a case where, from all reactions involved, a certain quantity of energy can be effectively derived for blast purposes. What is the optimum arrangment for its generation? The degree of damage at a given point in space increases with the energy density at that point and likewise the amount of it used up will similarly increase, and, thus, the amount left to cause demolition at points further from the bomb will diminish. In view of this, the optimum arrangement would be to have the energy liberated at just the rate required to cause the demolition desired, and no faster. This would increase the damage radius of the charge, as excessive energy would not be wasted in undue powdering or fracturing of demolished structures and would be available for demolition further from the charge. Altho, for reasons of a physico-chemical nature, this ideal situation probably could not be realized and a compromise towards initially higher generation rates would be necessary, the qualitative reasoning definitely shows it is unwise to have substantially all the energy liberated during detonation.

Considering the above qualitative arguments, and the fact that if oxygen deficient material in the explosive can be made to oxidize (during the explosion by utilizing atmospheric oxygen) it thereby effectively increases the bomb charge weight, a probable method of improving bomb blast is made apparent. Trial of aluminized explosives confirmed the above idea, and, for instance, it was found that a 75/25-TNT/aluminum mixture produced blast pressures and impulses 11 and 16% greater respectively than the same volume of TNT alone. Addition of 28% aluminum to amatol improved its impulse by about 14%, while a 21/79-tetryl/aluminum mixture had an impulse 25% above straight tetryl. (See Table III at rear). It might be added that the weight of oxygen utilized in the afterburning of such explosives is the effective increase in the bomb filler weight mentioned above, and represents weight not requiring transport since it is supplied at the point of air-blast demolition.

The success attained, by the use of oxygen deficient materials such as aluminum, in enhancing blast effect lead naturally to the consideration, based on heats of combustion, of several other materials. For instance, a comparison of the heats shown below indicates that many other materials are worth considering.

Fig.16

Material	Ht. of Combustion - Kcal/gm
Magnesium (d= 1.74)	5.99
Aluminum (d= 2.7)	7.49
Carbon (d~2)	7.86
Asphalt	9.53
Paraffin	10.34
Crude Oil	10.5
Gasoline	11.5

Since the last four materials have a density near 1 aluminum has the highest combustion heat per unit volume, but it was assumed possible that the others might be more efficient if more easily dispersed or volatilized or might be more reactive. Replacement of 40% of a blasting gelatin charge by aluminum produced a 25% blast improvement, while use of a 30% replacement of mixed aluminum and gasoline had a similar effect. Coal dust as a replacement had a lesser effect, and a mixture of coal dust and gasoline produced a diminution in the blast effect. Studies involving exploding charges in gas bags filled with air plus a vapor indicated a marked improvement when unsaturated, easily oxidized compounds such as benzene and acetylene were used, but little or no effect using materials such as propane, acetone or carbon disulphide. In general, results from different sources appear conflicting, and probably are dependent to a large extent on experimental conditions. For this reason, even tho aluminum looks like the optimum addend, further study of other materials appears desirable.

The foregoing studies lead further to trials of bombs made of aluminum or plastic, or containing explosive with combustible surrounds. This work was done in an effort to improve blast by slowing down the after oxidation reaction in the hope that it would take place over a greater volume and thus increase blast. The latter two types yielded disappointing results, but an aluminum bomb case improved blast. Using Minol and Comp B, in 4000-lb bombs, the following improvements were noted:

Fig. 17

Explosive	Case	Charge/Wt Ratio	Weight Saved-lb	Damage Area	Impulse Total	Impulse (a)
Comp B	1/8" steel	90	300	124	110	110
Comp B	5/16" Aluminum	93	550	142	118	114
Comp B	5/16" steel	83	0	100	100	
Minol	5/16" Aluminum	93	550	-	129	
Minol	5/16" steel	83	0	-	117	

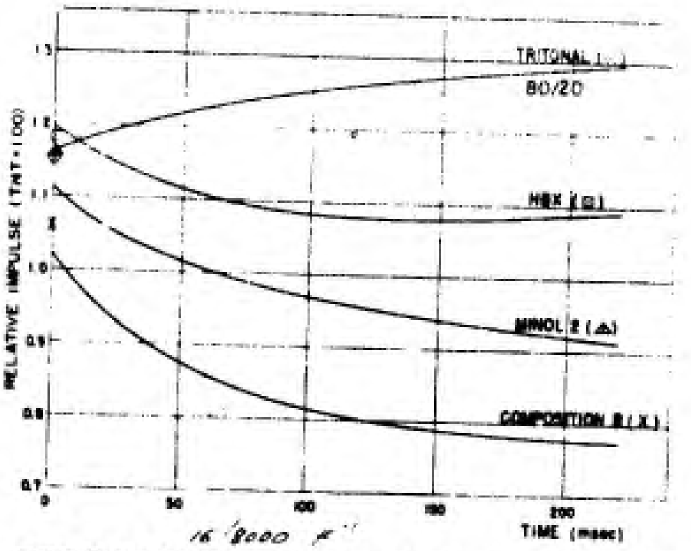
(a) Corrected for change in charge weight ratio.

Thus, the improvement was 18% in impulse of which 14% was attributable to the increase in charge-weight ratio and 4% to afterburning of the aluminum in air. This small increase due to afterburning indicates such a method of utilizing the combustible to be inefficient from this standpoint, although the overall improvement represents a worthwhile gain.

Certain miscellaneous information on air-blast might be appropriately mentioned at this point. APG has shown that two end initiation increases radial blast by about 20%, this being due, of course, to the Mach reflection, radially, of the blast waves travelling in opposing directions from each end of the bomb. The 100-lb M30 Bomb (TNT loaded) was found to produce a slightly greater blast effect when the charge was initiated by the standard tail booster than when an aerial booster running along almost the entire length of the bomb axis was used. This is interpreted to confirm the foregoing speculation on rate of energy liberation. Some work has been done in an attempt to locate the size aluminum powder that would produce optimum blast using Torpex. Powdered aluminum all on 40 mesh was found to give only 82% of the pressure and 85% of the impulse afforded by finer grades ranging in size from about 150 mesh to 95% thru 200 mesh. Torpex made from 150 mesh aluminum was of interest as it had particularly low rifle bullet impact sensitivity. Minol 2, an explosive rather insensitive to initiation, gave pressures 0 to 10%

greater when shot capped with Comp B and impulses 5 to 16% greater. The low values were obtained using 13 lb charges and the high values with 46 lb charges, which is indicative of Minol's relatively poor capability to propagate.

A fairly extensive study was also made of the effects of explosions in spaces with only small venting, i.e., confined air blast. The findings showed that here also, afterburning contributed quite significantly to the blast, as in the case of unconfined air explosions, but that the proportion of energy so generated was even greater. Thus, while Minol and Comp B are definitely superior to TNT in open air explosions, under confinement TNT offers a more sustained blast than either. Fig. 18 shows the relative impulses afforded, in a space with small vent, by four explosives, at various times after explosion. All values given are relative to TNT. The British have studied to some extent a charge they term SBX (slow burning explosive), and have applied it to use under conditions of confinement and as a flashlite charge. SBX consists of a small charge of black powder or explosive, as a core, surrounded by various types of conbustible material such as coal dust, aluminum, gasoline, etc. British sources state that aluminum surround charges produce blasts equal to, or, above, that afforded by plain HE charges, but which are more sustained, especially in closed spaces. The curves(d)(SBX) and (b) (Tritonal) in Fig.19 show this to be the case.



POINTS AT t=0 ARE RELATIVE IMPULSE VALUES FOR AIR BLAST IN THE OPEN

Fig. 18

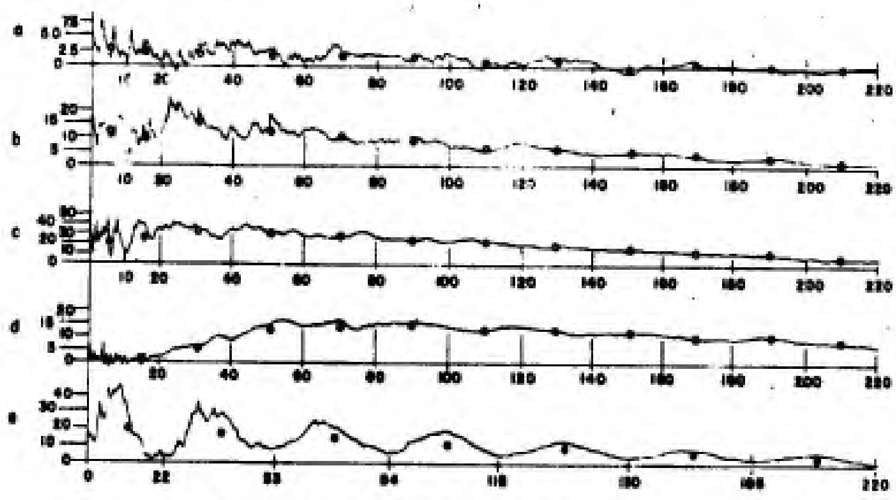


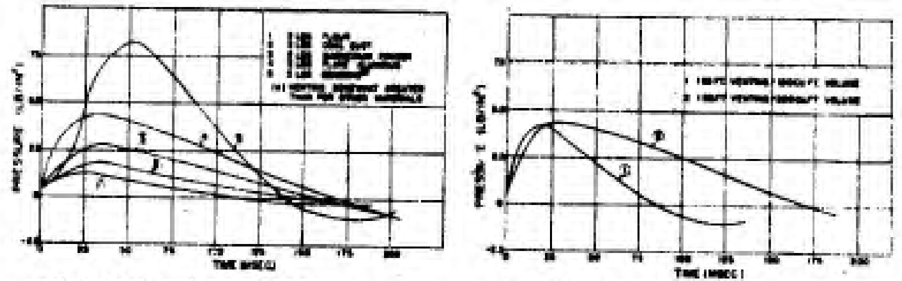
FIG. 3. TYPICAL PRESSURE VERSUS TIME OSCILLOGRAPH RECORDS (GRUBER).
THE HORIZONTAL TIME SCALE IS THE SAME THROUGHOUT. THE NUMBERS REPRESENT MILLISECONDS. THE VERTICAL PRESSURE SCALE IS INDICATED ON THE LEFT IN POUNDS PER SQUARE INCH.

(a) 2 LB OF TRITONAL, RIGHT-WING GAUGE
(b) 12 LB OF TRITONAL, RIGHT-WING GAUGE
(c) 45 LB OF TRITONAL, RIGHT-WING GAUGE
(d) 12 LB OF ALUMINUM-GASOLINE, RIGHT-WING GAUGE
(e) 12 LB OF TRITONAL, CORNER GAUGE

CIRCLED POINTS REPRESENT MEASURED AVERAGE PRESSURE FOR THE INTERVALS

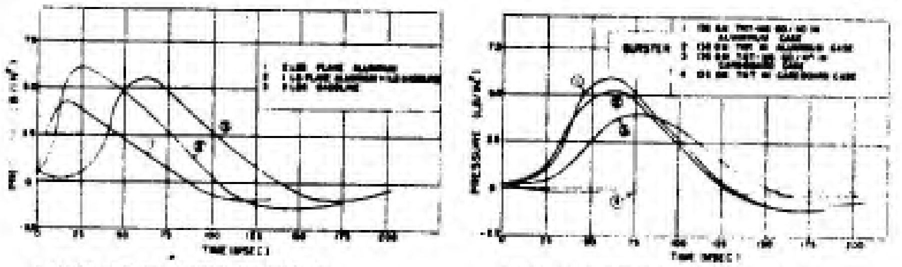
Fig. 19

Fig. 20 illustrates the effectiveness of various materials as components of SBX charges, and also details the effects of amount of venting, type burster, and of mixing gasoline and aluminum.



a COMPARISON OF TYPICAL SBX MATERIALS

b EFFECT OF CHANGING VENTING AREA WITH FLAKE ALUMINUM



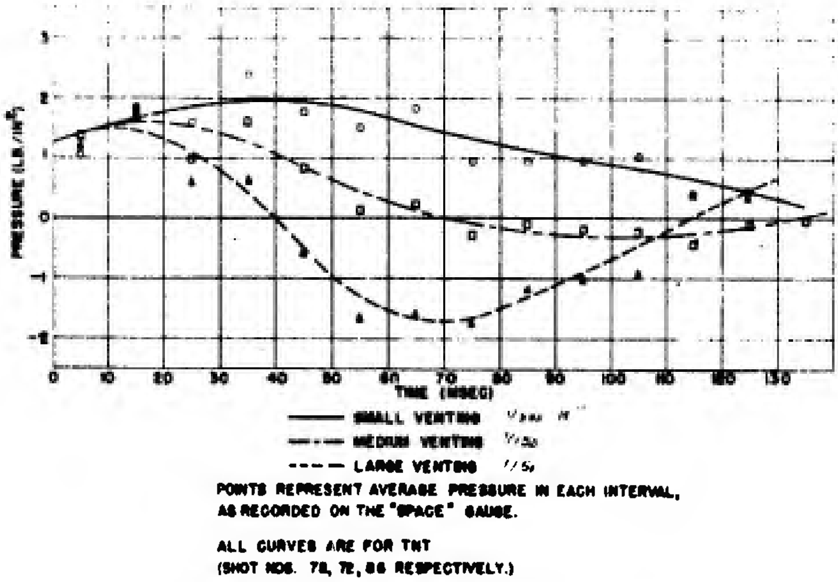
c EFFECT OF MIXING ALUMINUM AND GASOLINE

d EFFECT OF NATURE OF BURSTER WITH GASOLINE

FIG. 9 PRESSURE VERSUS TIME CURVES FOR SBX UNDER VARIOUS CONDITIONS
NORWOOD

Fig. 20

Fig. 21 shows the effect of venting on the pressure time curve, which in the case of large venting illustrates the periodicity of the blast which would also become evident in the case of the other two curves were they extended. This periodicity gives rise to the multiple punch effect mentioned earlier. Evidently, SBX charges would provide excellent means for demolition from within. The above data, it is believed, also support the previous belief that more blast work with combustibles other than aluminum is warranted. They also indicate that in all air blast work more study should be expended to determine an optimum ratio of energy released during and after detonation. Work on this subject is at present under way at the Arsenal.



THE EFFECT OF VARYING VENTING AREA UPON THE SMOOTHED PRESSURE-TIME CURVE (NORWOOD).

Fig. 21

It is apparent from the blast values presented in the foregoing that a series of explosives will not necessarily be ordered similarly for free air blast and for confined air blast. There are two other conditions of importance under which explosions may occur, underwater and underground, and again performance under these conditions need not correlate with that in air. However, the similarity between free air blast and that under water and underground is closer than between the latter two and confined air blast as shown in Fig. 22.

Fig. 22

Explosive	Free Air	Confined Air	Under Water	Under Ground
Torpex	1	-	1	-
HBX	2	2	2	1
Minol	3	4	3	2
Tritonal	4	1	5	3
Comp B	5	5	4	4
TNT	6	3	6	6
Amatol	7	-	-	5

No 1 = best; higher numbers represent poorer performances.

The reason for this difference between the correlations just referred to resides in the fact that after burning is far more important in the case of confined air blast than for free air blast. In the former case, after burning is of such importance that practically complete combustion is realized and performance is closely proportional to the heat of combustion. (Fig. 23)

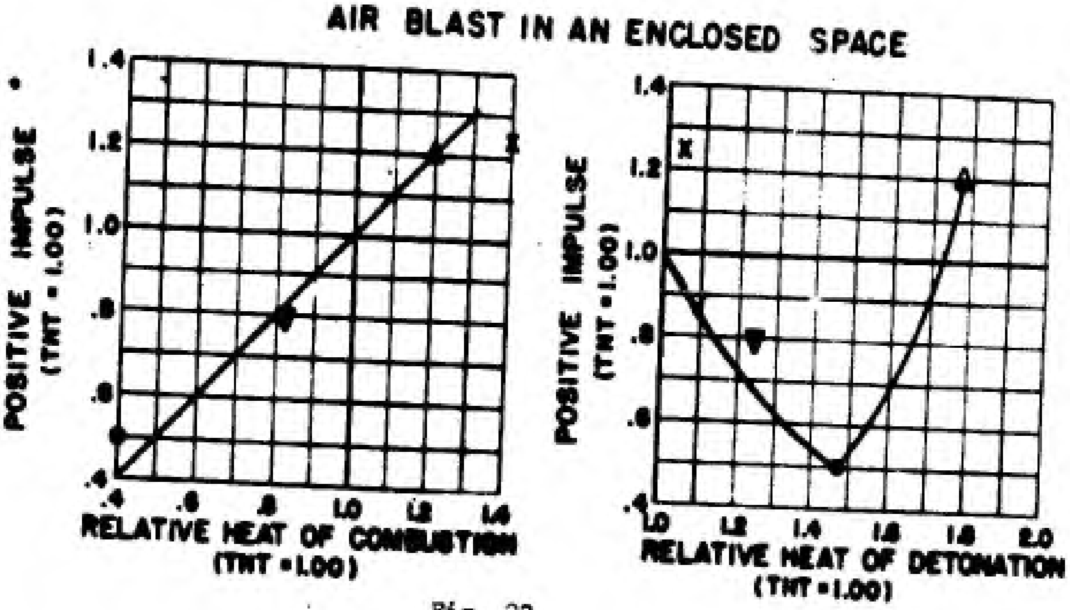


Fig. 23

In the case of underwater blast the performance is quite dependent on the heat developed during the detonation proper, as indicated in Fig. 24,

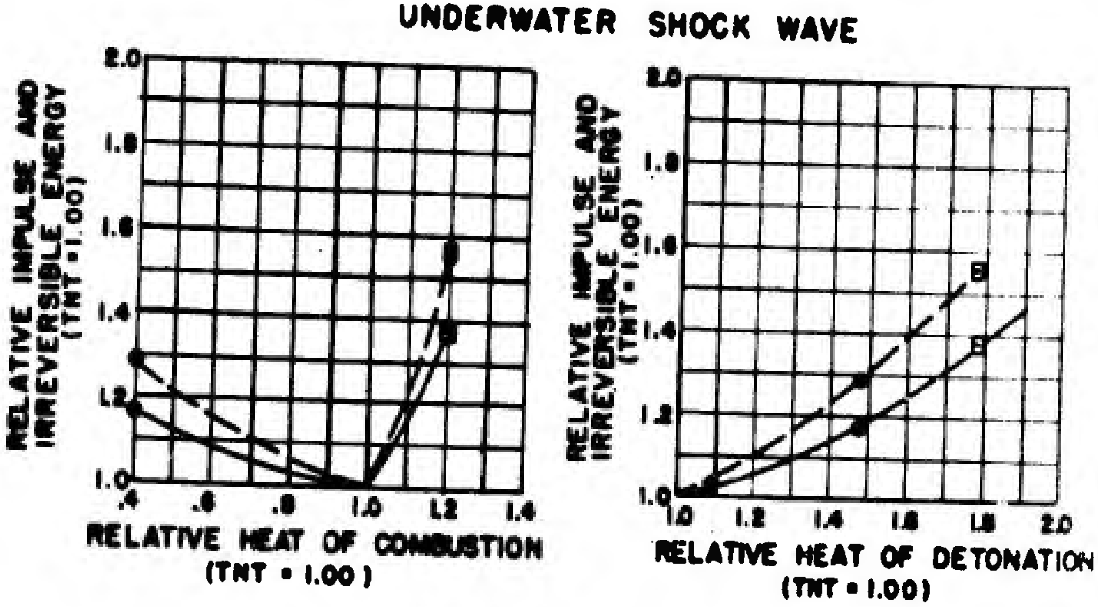


Fig. 24

but cannot always be proportional to it as Tritonal (not shown in the figure) out performs TNT. This would not be the case if detonation heat were the sole criterion as the detonation heat of TNT is the greater. Thus, energy generated after detonation also plays some part. This energy, since air is not present, must be derived from interaction between the products and aluminum resulting in the oxidation of aluminum with resultant liberation of energy. The quantity of energy so produced must be limited, however, as Tritonal is outperformed by Comp B, which is not the case in underground explosions where a very limited amount of air is involved, and somewhat better confinement is afforded. In the latter case, the energy contributed by the after reactions is the greater, but is exceeded by that involved in free air explosions. This is indicated both by the effectiveness of underground amatol explosions as compared to those of TNT, which is superior in free air; and also by a consideration of the physical conditions involved.

In work currently underway at this Arsenal, the prime interest involves the development of filler of improved blast and decreased sensitivity to shock. As a yard stick by which to gage progress in such an investigation, there is need of a rapid simple test by which to evaluate blast. Of course, the proof of the pie is in the eating, and likewise actual blast determinations represent the best criterion short of field trials, and they will at the appropriate time be resorted to. Blast measurements are, however, relatively expensive and time consuming. For preliminary evaluational purposes, a rapid, simple inexpensive test, the Sand Test, is available. It involves exploding a small charge of explosive (0.4 gm) within a volume of sand, and determining the weight of sand crushed. At first glance the results might not be expected to correlate well with air blast, but when it is remembered that the sand volume comprises sand grains and air voids in about a 1:1 ratio, with a free air space a short distance above the charge (i.e., above the sand's upper level) the comparison appears more reasonable. Fig. 25

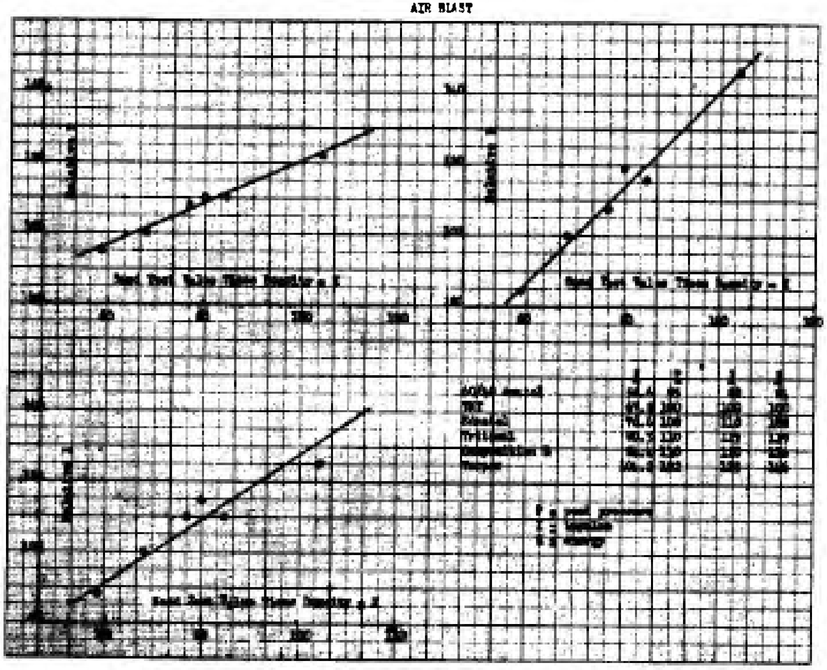


Fig. 25

indicates the correlation between the results of the Sand Test (on a volume basis) and blast pressure, impulse and energy. As might be expected, the Sand Test is a better indication of peak pressure than impulse, or energy which is roughly proportional to peak pressure times impulse.

In closing, it might be emphasized that, although the lecture was organized with a view to presenting a qualitative description of blast effects, it has been directed towards disclosure of the most fruitful field of study for future blast work. This involves investigation of the importance of the amount of energy generated during and after detonation. Since heat of detonation bears a rough direct relation to rate of detonation, it is believed that the contemplated study can be effected through work with the appropriate type compositions having various rates of detonation.

TABLE I

BLAST CHARACTERISTICS OF VARIOUS EXPLOSIVES

Explosive	TNT = 100, for reference		
	Peak Pressure	Impulse	Energy
60/40 Amatol	95	85	84
50/50 Amatol	97	87	—
Amatex	111	113	—
Baronal	110	112	—
5/95 Cyclotol	-	100	—
60/40 Cyclotol	-	110	—
70/30 Cyclotol	-	109	—
DBX	118	127	138
Dentex	126	129	-
Ednatol	108	110	108
EL389A	107	101	-
EL389B	101	101	-
HBX	115	118	-
Methylite 20	96	99	-
Methylite 25	98	99	-
Minol 2	115	116	133
25/75 Pentolite	-	103	-
50/50 Pentolite	105	107	-
Pentolite D-1	-	103	-
PTX-1	111	109	-
PTX-2	113	113	-
RDX Comp B	110	110	116
RDX Comp C-3	105	109	-
RDX/Paraffin Wax/Al-72/13/15	-	113	-
TNT	100	100	100
Torpex 2	122	125	146
Trialen	117	120	-
Trialen D-1	113	119	-
Tritonal	110	115	119

TABLE II

COMPARISON OF BOMB EXPLOSIVES

Explosive	Torpex 2	HBX	Minol 2	Tri- tonal	RDX Comp B	TNT	60/40 Amatol
Composition - %:							
TNT	40	40	40	80	40	100	40
RDX	42	38	-	-	60	-	-
AN	-	-	40	-	-	-	60
Al	18	17	20	20	-	-	-
Wax D - 2^d	-	5	-	-	-	-	-
Cast Density - g/cc	1.71	1.65	1.64	1.70	1.60	1.55	1.56
Air Blast:							
Peak Pressure	122	115	115	110	110	100	95
Impulse	125	118	116	115	110	100	85
Energy	146	-	133	119	116	100	84
Air Blast Confined:							
Impulse	-	114	90	130	75	100	-
Under Water Explosion:							
Peak Pressure	116	113	108	105	110	100	-
Impulse	127	125	126	118	108	100	-
Energy	153	145	140	119	121	100	-
Underground Explosion:							(50/50)
Peak Pressure	-	139	134	117	104	100	104
Impulse	-	150	139	127	97	100	104
Crater-radius cubed	-	151	147	136	107	100	104
Fragment Velocity	118	109	107	102	114	100	103
Plate Dent Test	119	106	66	93	131	100	-
Ballistic Mortar Test	138	126	141	117	134	100	-
Rate of Detonation	7500	7400	5800	6700	7800	6800	6040

TABLE II (contd)

Explosive	Torpex 2	HBX	Minol 2	Tri-tonal	RDX Comp B	TNT	60/40 Amatol
Heats of - Kcal/cc							(50/50)
Explosion	3.08	-	2.66	3.05	1.98	1.64	1.50
Combustion	6.40	6.70	5.19	7.63	4.49	5.62	3.09
Impact Sensitivity							
Drop Test	42	75	47	88	46	100	-
Dent Test	85	100	-	-	-	95	-
Rifle Bullet Impact Test % - Unaffected		72 (b)					
Cal. 30 - 2" x 3" long bombs	0 (b)	100 (a)	0 (b)	60 (b)	95	100	-
					-	1	-
Large Scale c	3	1-2	3	-	3	1	-
Bomb Drop Test c	4	2	4	2			

a. 12-325 M Al

b. T100 M Al

c. 1 = least sensitive

d. 84/2/14 - wax/lecithin/NC of 11.8-12.3% N, 1/2 sec

TABLE III

EFFECT OF ALUMINUM ON PERFORMANCE

I. BLAST P = peak pressure; I = impulse

a. TNT

% Al	Density - g/cc	P	I	Remarks
0	1.58	100	100	Bomb tests put
15	1.68	108	112	Max at (a) 32.5%
20	1.69	108	112	Al for I in British
25	1.73	111	116	500 lb. MC Mk III, (b) at
30	1.76	108	116	25% by U. S. work

b. Minol

% Al	I	Remarks
0	73	500 lb MC Mk III British bomb
10	90	
20 (Minol 2)	100	
24	102	
28	104	

c. Tetryl

% Al	P	I	Remarks
0	100	100	Small scale test
79	120	125	

d. Torpex

			500-lb MC Bomb		
% RDX	% TNT	% Al	Density-g/cc	P	I
50	50	0	1.61	100	100
44	44	12	1.66	114	112
41	41	18	1.69	117	120
38	38	24	1.72	118	122
35	35	30	1.75	116	127
29	35	36	1.77	111	124
23	35	42	1.81	104	123

e. Miscellaneous

	% RDX	% TNT	% Al	P	I
Torpex 2	42	40	18	100	100
Trialen	15	67	18	94	95
	15	60	25	98	98
	15	55	30	98	96

TABLE III (contd)

II. Lead Block Test:

a. TNT

% Al	Expansion - cc
0	100
10	116
18	123
20	123
30	98

b. Ammonium Nitrate:

% Al	Expansion - cc	Rate
0	100	100
3	102	124
7	112	147
16	180	148
21	196	158
25	209	
30	202	138
40	177	

c. PETN

% Al	Expansion - cc
0	100
15	130
32	135
41	102

III. Calorimetric

a. TNT

% Al	Q = Ht of expl	V = Gas Vol
0	100	100
5	120	80
10	125	80
15	160	67
20	178	57
25	195	47
30	210	40