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Explosives
AND
TERMINAL BALLISTICS

A REPORT PREPARED FOR THE AAF SCIENTIFIC ADVISORY GROUP

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Dr. von Karman gathered about him a group of American scientists from every field of research having a bearing on air power. These men then analyzed important developments in the basic sciences, both here and abroad, and attempted to evaluate the effects of their application to air power.

This volume is one of a group of reports made to the Army Air Forces by the Scientific Advisory Group.

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PART II

PROPERTIES OF HIGH EXPLOSIVES

By

D. P. MacDOUGALL

PART II

PROPERTIES OF HIGH EXPLOSIVES

3 APRIL 1945

INTRODUCTION AND SUMMARY

The purpose of this report is to give a brief summary of the present status of our knowledge concerning the properties and utilization of military high explosives. Attempts are also made to give estimates concerning the behavior of several mixtures and compounds which are not now in use, but might be considered for use in the future.

This report does not contain a thorough discussion of the terminal ballistics of explosive-loaded munitions. However, this subject is discussed briefly in order to provide a basis for comparison of different explosives. Particular attention is paid to the performance of high explosives in blast bombs, partly because this phase is probably of most interest to the Air Forces, and partly because the action of explosives in producing blast has been more thoroughly investigated than other types of action.

Of the explosives in military use today, HBX or desensitized Torpex appears to be the best all round filler for bombs. A bomb loaded with HBX will produce an area of destruction about 45% greater than that from the same bomb loaded with TNT. On the other hand, HBX is sufficiently stable and insensitive to shock to be used in G.P. Bombs.

If, in the future, conditions arise which permit the use of explosives of much greater shock sensitivity than TNT (for filling some sort of robot bomb, perhaps), the best bet, if the comparison is made on a volume basis, would appear to be an explosive of the Torpex type, but with a larger percentage of aluminum. One might hope to achieve, with such an explosive. a damage area twice that of the same volume of TNT. If the weight, rather than the volume, of explosive is chosen as the basis for comparison, the most effective explosive would be a stoichrometric mixture of liquid hydrogen and liquid oxygen. This mixture might give a damage area four or five times as great as that produced by the same weight of TNT. Because of the low density however, this mixture would not be very effective on a volume comparison.

There is some discussion in the report of SBX, by which is meant an explosive consisting entirely of a fuel (plus a small amount of conventional H.E. to give dispersion) and which utilizes atmospheric oxygen in the detonation reaction. Since only the fuel must be carried, the amount of energy liberated per unit weight is, in general, large compared with the value for a conventional high explosive, where, in a sense, both the fuel and the oxygen are carried together. The analysis given in the body of the report suggests that gasoline, used as SBX, might put somewhat over twice as much energy into the blast wave as the same volume of TNT. On a weight basis, the comparison is even more favorable to the SBX. However, experiments with SBX have shown that while it is effective in confined spaces, it is very ineffective in the open. This is probably due to a slow reaction between the fuel and the oxygen of the air, which may be overcome in the future. This is a subject which might generously repay future investigation.

GENERAL DISCUSSION

There are many jobs which a high explosive may be called upon to do, and there is not now, and probably never will be, a single explosive which is best for all uses. The properties desirable in the explosive used as the filler of an armor-piercing shell are different from those required for the filling of a depth charge, and a demolition explosive must meet still other requirements. In the present discussion, most attention will be paid to explosives which can be used as fillings for aerial bombs, both because such explosives are of greatest interest to the Air Forces, and because, on a tonnage basis at least, they are the most important. Even in a single type of munition, such as a general purpose bomb, the explosive produces damage by at least three different methods, air blast, fragments, and earth shock. It is not necessarily true that a given explosive is equally effective in producing all three types of damage. In selecting an explosive for a particular munition, therefore, it is important to have available information concerning its effectiveness in the specific type of action involved.

A high explosive is a material which can be induced, at a predetermined time and place, to explode or detonate. In the process of detonation the explosive is converted rapidly, in a period of a few microseconds, into a large amount of gas at a high temperature and pressure, with the release of a large amount of chemical energy. An explosive must therefore be a material of controlled stability. If it is too stable, it will be impossible to make it explode, while if it is not stable enough, it may explode before one is ready for it to do so. Due to its latent instability, every explosive can be made to decompose, with varying degrees of violence if heated sufficiently. However, if the material is to be of practical utility, it must not undergo appreciable decomposition during extended periods of storage at temperatures which might be encountered in magazines, storage depots, holds of ships, etc. An explosive which does undergo such decomposition during storage is undesirable because this decomposition may lead either to premature explosion or to loss of performance. One important requirement for a military explosive, then, is that it must possess adequate chemical stability. There is no hard and fast rule for deciding whether or not stability is adequate. The ideal is that it withstand the very highest temperatures to which an explosive might be subjected, for periods of time upward of twenty years without appreciable change. However, many materials are accepted for use which are much less stable than this, particularly if they possess other advantages. The only completely reliable way to find out whether an explosive will stand a temperature of 65°C, say, for twenty years, is to keep the explosive at this temperature for twenty years. To save time, tests are carried out in the laboratory at considerably higher temperatures for shorter periods, and by this means, a fairly reliable estimate of the stability of a new explosive can be obtained in the course of a few months.

All explosives can be made to detonate by subjecting them to a severe enough mechanical shock, but some are set off by this means much more readily than others.

For an explosive to be suitable for a given purpose it must withstand, without detonating, all of the mechanical shocks to which it may be subjected before the time for its planned detonation. The mechanical shocks may be accidental, and all explosives must be capable of standing a certain amount of rough handling during shipment, loading, etc. In addition, in many munitions, the explosive receives a variety of shocks and stresses in the course of normal operations, such as the forces of setback which occur when a shell is fired from a gun. The intensity of these planned shocks varies widely from munition to munition. In an armor-piercing shell, for example, the explosive must not only withstand the setback forces, but it must not detonate or burn when the shell passes through a piece of armor plate. In a high capacity aerial bomb, on the other hand, an instantaneous fuse is normally used, so that the filling is expected to detonate immediately on hitting the ground, and hence the requirements with regard to insensitivity to shock are very much less. Once again, the only completely satisfactory way to determine whether a particular explosive has a degree of insensitivity to mechanical shock adequate for the contemplated use is to carry out actual performance tests of the explosive in the full-scale munition.

Again, however, at least a partial answer can be obtained from small-scale laboratory tests. These tests involve delivering to small samples of the explosive mechanical shocks of carefully controlled type and intensity. The most widely used test consists of determining the height from which a standard weight must be dropped on a standard sample of explosive to produce explosion. The absolute value of this height has no great significance, but it does place the explosive on a scale determined by heights similarly determined for other explosives. If, for example, explosive A has been widely used as the filling for a particular munition, and has been found to have adequate insensitivity, and a new explosive B is found in the drop-weight test to be more difficult to explode than explosive A, then there is a good probability that explosive B will also be adequately insensitive for the munition. If its other properties, or its availability, make its use attractive, then it will be worthwhile going to the trouble of carrying out tests in the actual munition.

A new explosive which is being considered for use as a filling for aerial bombs will normally be tested in the laboratory with regard to sensitivity to friction and impact, and to bullet impact. If it appears to have satisfactory insensitivity for the purpose in mind, the full scale sensitivity tests include firing various types of small arms ammunition at the loaded bomb, and dropping the bomb from various heights on a hard surface.

In addition to adequate stability and insensitivity to shock, the third important attribute of an explosive is its performance. Since, as pointed out previously, explosives may do useful work in a number of different ways, no one type of performance test will suffice to give a general evaluation of the effectiveness of an explosive. The three principal factors which determine the potency of an explosive are: the amount of energy liberated during detonation, the volume of gas produced, and the rate at which the conversion from undetonated explosive to final products takes place. For one application, one of these factors may be of greatest importance, while in other applications, another one may be more important. This is basically the reason why it is not possible to assign a single figure of merit to a given explosive. In a cavity charge, such as the head of the bazooka, for example, the quantity which appears to determine the effectiveness of the explosive filling is the pressure produced in the head of the detonation wave. To obtain the highest possible pressure, the amount of energy and gas liberated should be high, but the conversion should also be as rapid as possible. For this type of action, the aluminized explosives are less effective than certain others which liberate less energy, due to the fact that the reaction involving aluminum takes an appreciable amount of time, and so that the peak pressure in the detonation wave is less than it would be if the reaction were instantaneous.

Now, coming specifically to the performance of aerial bombs, it may be noted that these bombs can produce three destructive agents, namely air blast, fragments traveling at high velocity, and, if they explode under ground, earth shock.If the bomb explodes under water near the hull of a ship, the agent of damage is a shock wave in the water. Of these agents, perhaps the most important is air blast. When a bomb explodes, the rapid expansion of its contents produces a compression wave in the air, or a shock wave. (A shock wave is similar to a sound wave, but of much greater intensity.) In this shock wave, the pressure rises essentially instantaneously from normal atmospheric pressure to a maximum value, at the front of the wave, and then falls off in a roughly exponential fashion, reaching atmospheric pressure at some distance behind the front, and then continuing to fall to a minimum value which is appreciably below atmospheric pressure, finally reaching normal pressures again at a greater distance behind the front. This shock wave can be characterized by specifying its peak pressure, the momentum or impulse contained in it per unit area, and the energy content per unit area of the front. The positive impulse or momentum is simply the integral of the excess (above atmospheric) pressure against the time for that part of the wave in which the pressure is above atmospheric. The energy content is found by a similar integration of the square of the excess pressure times the time. The magnitude of the peak pressure and the momentum depend on the weight and type of explosive and on the distance from the point of explosion. For most types of structures, the quantity which determines whether or not they will be damaged by a shock wave is the positive impulse or momentum. However, if the shock wave is of very long duration, which may be due to its being produced by the detonation of a very large quantity of explosive or by the explosion of a very slow acting explosive (especially SBX, mention of which will be made later), then the damage tends to depend on peak pressure, as in the static case.

However, for conventional explosives in bombs of normal size, the quantity which determines damage is approximately equal to the positive impulse. The impulse, I, changes with weight of explosive and distance according to the following equation:

$$I = k \frac{W^{2/3}}{r} \qquad (1)$$

where W is the weight of the explosive charge and r is the distance from the point of detonation. The constant k depends on the nature of the explosive and on the thickness of the case. A heavy-cased bomb gives a weaker shock wave than the same weight of explosive in the form of a bare charge, because a considerable fraction of the explosive energy is given to the fragments of the case, if it is present. The effectiveness of a given explosive in producing damage by air blast can be expressed by giving the value of the impulse produced at a standard distance by a standard weight of charge. It is more common, however, to quote the impulse relative to that produced by the same weight or volume of some standard explosive at the same distance. The statement above, that damage depends on impulse, means that for a given type of construction, a certain class of damage (Class B damage, for example) will occur at all points where the impulse is equal to or greater than a certain quantity. Since area depends on the square of distance from the bomb, the relative areas of a certain class of damage for two different explosives will be proportional to the square of the impulse ratio for the two explosives. For example, a suitable way of expressing the effectiveness of Torpex as an explosive for causing damage by air blast, is to say that the area of damage is approximately 60% greater than that produced by the same volume of TNT.

For producing air blast, explosives containing aluminum are in a class by themselves. The very high energy of reaction of aluminum with the oxygen contained in the explosive more than compensates for the reduction in volume of gas produced. The overall reaction involving aluminum is not as fast as that for a pure explosive compound, but for bombs of any reasonable size, the duration of the shock wave is sufficiently great so that, while a slow reaction may result in a lower peak pressure, the energy is all liberated before the production of the shock wave is completed and so it is all effective.

The effectiveness of a bomb in producing damage by fragments depends on the number and average weight of the fragments produced and on the velocity of the fragments. The situation is very complicated because the size of the most effective fragments depends on the type of target being attacked. For personnel and light materiel, a large number of small fragments will have the greatest effect. For heavier targets, the fragments should be larger, and will consequently be fewer. With regard to velocity of fragments, there is a fair correlation between fragment velocity and air blast intensity for different explosives. It has been found that when the explosive in a shell or bomb detonates, the case is not immediately ruptured, but swells a considerable amount first. For this reason, there is an appreciable time period during which the highly compressed gas in the bomb can impart velocity to the case. However, the time available is not so long as for producing a shock wave, and in some cases, it is found that an explosive which is very effective in producing air blast is less effective in producing high-velocity fragments. Minol, which is aluminized Amatol, is probably a case in point. In general, it can be stated that the effectiveness of a bomb in producing fragment damage depends at least as much on the ratio of case weight to charge weight as it does on the type of explosive, and it is not possible to give a specific figure to represent the fragment damaging power of an explosive.

The ability of an explosive to produce earth shock and cratering action has not been very thoroughly investigated. In general, it appears that the order of effectiveness of different explosives is about the same as is found when air blast is considered, except that explosives containing ammonium nitrate are more effective as cratering agents than they are in producing air blast.

The mechanism by which an explosive produces an underwater shock wave is not very different from that by which it produces an air shock wave. However, there are indications that during a bomb explosion in air, there is some energy liberated by reaction with the oxygen of the surrounding air, whereas, this cannot happen under water. Probably for this reason, the relative effectiveness of different explosives in doing underwater damage is not quantitatively the same as that for air blast damage, but the two ratios are in general not very different.

SOLID EXPLOSIVES

The detonation of an explosive compound is essentially an internal combustion; that is, the fuel and the oxygen for its combustion are contained in the same molecule. Since the same atoms are present both before and after reaction, detonation must be a rearrangement of the atoms so as to form more stable, stronger chemical bonds. This is accomplished in practice by having the oxygen in the explosive connected to the rest of the molecule through nitrogen atoms. After reaction, the oxygen is found to be directly attached to carbon and hydrogen atoms. For this reason, all of the conventional explosive compounds contain nitrogen, either in the form of nitro groups or nitrate groups. The compounds are made by allowing nitric acid to react with the appropriate substance, usually a compound of carbon and hydrogen, with or without some oxygen.

Explosives as used may be pure explosive compounds, or they may be mixtures of two or more explosive compounds, or they may be mixtures of one or more explosives with a nonexplosive. In general, a high explosive must contain a certain proportion of an explosive compound. A substance such as black powder, which is a mixture of fuel and oxidizing agent, can react vigorously if ignited, but is believed to be incapable of a true detonation. In the paragraphs which follow, brief discussions will be given, first of the important explosive compounds used in military explosives, and then of the important mixtures.

PURE COMPOUNDS

TNT or Trinitrotoluene.

This explosive is undoubtedly the most important single explosive in use today. It is made by the nitration of toluene. Toluene was formerly obtained only from coal tar, but is now made from petroleum and is available in large quantities. It is a compound melting at about 80°C, and thus can be melt-loaded by the use of steam, which is one of its attractive features. It is a very stable material, as explosives go. If properly purified, it can be stored for many years without deteriorating. As made during World War I, it usually contained appreciable amounts of low-melting impurities, which resulted in the exudation of an inflammable liquid during storage. However, the highly purified material being made today does not show this effect. TNT is a highly insensitive explosive and on this score is suitable for most applications. However, it does not have the very high degree of insensitivity which is required for filling A. P. shells and bombs. It is the standard filling, or one of the standard fillings for the following munitions: all aerial bombs, except armor piercing; all calibers of high explosive shell; demolition blocks; depth charges and depth bombs; mines.

With regard to performance in various weapons, TNT is a moderately powerful explosive but weaker than many of the newer materials. It is difficult to describe the performance of an explosive by giving absolute numerical figures. It is simpler and just as satisfactory, as far as comparison among different explosives is concerned, to pick one explosive as a standard and measure the performance of other explosives under various conditions in terms of the performance of the standard explosive. Normally, TNT is the explosive which is taken as the standard material. The ratios to other explosives are of two general types. One may use the ratio of the damage (of some specified sort) produced by a given weight of the explosive under consideration, to the damage produced by the same weight of TNT. On the other hand, it is sometimes more convenient to use the ratio of weights of the two explosives necessary to produce equal damage. Since the numerical values of the two kinds of ratio are in general different, one should be careful to note which one is being used.

Tetryl or Trinitrophenylmethylnitramine.

This compound can be made by several methods. The chief starting material is benzene. This explosive is definitely less stable than TNT, but its stability appears to be adequate. It is appreciably more sensitive to shock than TNT. Its melting point is about 130°C, at which temperature it undergoes rather rapid decomposition, so that it cannot be melt-loaded. It is generally loaded by pressing into the container. It is used as the filling for certain small caliber shells, such as 20 mm, but is in general too sensitive for use as the main filling of larger munitions. It finds its widest application as a booster explosive. That is, a pressed pellet of tetryl picks up detonation from the detonator, and in turn sets off the main charge. The very insensitive explosives cannot be set off directly by a detonator. It is appreciably more powerful than TNT, but where used as a booster, it represents such a small fraction of the total charge that its power does not make much difference.

Picric Acid or Trinitrophenol.

This explosive is made by the nitration of phenol, which in turn is made from benzene. This explosive itself is not used by this country, except as an intermediate in the manufacture of ammonium picrate, but it is in use by certain other countries. Picric acid has a rather high melting point for melt-loading, 122°C. However, by using rather high pressure steam, it can be so loaded. Picric acid is slightly more powerful than TNT, and is somewhat more sensitive, although less sensitive than tetryl. Since it is a rather strong acid, it can react with metals to form salts, which are quite shock-sensitive. The tendency to form sensitive salts and its high melting point are two of the undesirable features of picric acid. However, out of contact with metals, it is a very stable material.

Ammonium Picrate or Explosive D.

This explosive is the ammonium salt of picric acid, from which it is made. It has a very high melting point, and is therefore always pres-loaded. Its most important characteristic is its great insensitivity to mechanical shock. It is also a very stable material, and unlike picric acid, it does not tend to react with metals. It is somewhat less powerful than TNT. Its chief use is as the filling for armor piercing projectiles and bombs. In fact, for large A. P. shells, it is the only explosive now in use by our armed forces which is sufficiently insensitive.

RDX, Cyclonite, or Cyclotrimethylene Trinitramine.

This compound has been known for many years, but has come into manufacture and use as a military explosive only during the present war. It is made by the reaction of nitric acid with hexamethylene tetramine or hexamine. The latter is formed by the reaction of ammonia and formaldehyde. The process developed by the British involves the straight nitration of hexamine; this process, with minor modifications, is used in this country at the Wabash River Ordnance Plant. Another process, the combination, or anhydride process, was developed in this country, and is in use at the Holston Ordnance Works. In this second process, the yield of RDX per pound of hexamine is considerably greater, and the consumption of nitric acid is much smaller. RDX is a high-melting compound, melting around 200°C, and cannot be melt-loaded. As a matter of fact, it is rather sensitive to shock, being somewhat more sensitive than tetryl, and consequently is always used in mixtures either with other explosives of lower sensitivity or with nonexplosive desensitizers. Despite the fact that RDX is a very energy-rich explosive, it is very stable, approaching TNT in this respect. It is a very powerful explosive, approximately equivalent to nitroglycerine. However, as an explosive to produce air blast, it is exceeded in effectiveness by some of the aluminized explosives.

PETN or Pentaerythritol Tetranitrate.

This compound is made by the nitration of pentaerythritol, a polyhydric alcohol produced synthetically. This compound is a nitrate ester, whereas all of the explosives mentioned above are nitro compounds. Like other nitrate esters, it is not very stable, but sufficiently so for most purposes. It is somewhat more stable than nitrocellulose, which is the chief constituent of smokeless powder. PETN is a very shock-sensitive explosive, being more sensitive than RDX. As a result, it is used in the pure form only in specialized applications, such as the base charge for some detonators and as the core of detonating cord or primacord. It is a powerful explosive, being in this respect only slightly inferior to RDX. However, its disadvantages with respect to RDX are that it is more sensitive and less stable. It finds application principally as Pentolite, which is a mixture of PETN and TNT.

SOLID EXPLOSIVE MIXTURES.

Amatol.

The best known explosive of this class is undoubtedly Amatol, which is a mixture of TNT and ammonium nitrate in varying proportions. The 50/50 and 60/40 mixture with TNT can be melt-loaded as a slurry, in which the solid ammonium nitrate is carried by the molten TNT. An 80/20 mixture is sometimes used, but this cannot be poured. For most applications, and in particular for producing air blast and fragmentation, Amatol is somewhat less effective than TNT. For air-blast damage, the area of damage for Amatol is about 80% of that from an equal weight of TNT. However, for cratering action and perhaps for producing earth shock, when a bomb explodes underground, Amatol is somewhat more effective than TNT. The presence of ammonium nitrate in Amatol makes it a very hydroscopic explosive, and when moist it is quite corrosive in contact with most metals. This necessitates very careful sealing of an Amatol charge against moisture. Because of this hydroscopicity and rather low power, Amatol is considered as a substitute for straight TNT when the latter is scarce. If TNT is in good supply, Amatol is not used for most applications.

Composition B.

This explosive consists of a mixture of RDX and TNT, normally in the proportion of 60% of RDX and 40% of TNT. One part of wax per hundred parts of explosive is normally added to give some desensitizing action. The mixture with wax is called Composition B, while if the wax is omitted, the explosive is called Composition B-2. There is sufficient TNT in this mixture so that at temperatures above the melting point of TNT, it can be poured as a slurry. The explosive is fairly insensitive to shock, but of course more sensitive than TNT. It is generally considered to be equivalent to picric acid in this respect. The stability of the mixture of RDX and TNT is not as great as that of either of the pure components (a common situation in explosives), but the stability is more than adequate. Samples of Composition B have been stored for at least three years at a temperature of 65°C without noticeable decomposition. The pressure in the detonation wave is higher for Composition B than for any other explosive in actual military use, but pure RDX gives a higher detonation pressure. Since this is the most important factor in cavity charge performance, this explosive is excellent for such munitions. It also gives high fragment velocity when used in bombs and shells, about 10% faster fragments than TNT. However, as an explosive for producing blast damage, it is of intermediate effectiveness, being superior to TNT, but inferior to the aluminized explosives. In aerial bombs, Composition B gives about 25% greater area of damage than does TNT in the same bombs. If the choice lay solely between TNT and Composition B, the latter would be the choice, since it has better performance and adequate insensitivity, although it is more sensitive than TNT. However, there are other fillings that are still better.

Pentolite.

This explosive is a 50/50 mixture of PETN and TNT. It is normally loaded as a slurry, although for special purposes it can be pressed. It is more sensitive to shock than either TNT or Composition B. In fact, its sensitivity restricts its use to small munitions which will not be subjected to violent shocks. However, it is safe enough for handling, loading and shipping. The stability of Pentolite is inferior to that of straight PETN, and the explosive has a limited life when stored in very hot climates. However, during wartime, when there is a rapid turnover, its stability is probably adequate but near the lower limit. Pentolite has a high detonation pressure, but a little lower than that of Composition B. At present, Pentolite is chiefly used for filling various types of cavity charge munitions, such as the head of the bazooka. However, Composition B may replace it for this application. Pentolite is considered to be too sensitive to be used in aerial bombs.

Tetrytol.

This is a mixture of tetryl and TNT, usually in the proportion of 75% of tetryl and 25% of TNT. It can be poured and loaded as a slurry. This explosive has a stability and sensitivity intermediate between those of Composition B and Pentolite.

Its chief attractive feature is that it is an explosive which has a higher detonation pressure than TNT, but which does not use RDX. During most of this war, tetryl has been in good supply. Tetrytol is used chiefly as a demolition explosive, for which use it is appreciably more effective than TNT. Its disadvantages are appreciable sensitivity, mediocre stability, and tendency toward exudation in hot storage. The exudation results from the fact that the melting point of TNT is greatly reduced by the large solubility of tetryl in TNT. It has no features which make it attractive as a filling for bombs.

Compositions A and C.

These are mixtures based on RDX. Composition A contains 91% RDX and 9% wax. It is loaded by a pressing operation. Where press-loading facilities are available, it is an excellent filling for H. E. shell. It can also be used in small caliber A. P. shells. It is quite insensitive to shock, but not sufficiently so to be suitable for large caliber A. P. shells. Shells loaded with Composition A are considerably more effective than similar shells loaded with TNT or Explosive D.

Composition C, or rather the present version, Composition C-2, is a plastic explosive based on RDX. It contains somewhat under 80% of RDX, the remainder being a mixture of TNT, DNT oil and MNT. It is a very powerful explosive and for this reason and because it can be molded by hand, it is in great demand as a demolition explosive. It is also being tested in thin-walled rocket heads and bombs for use in attacking concrete pillboxes. The plastic nature of the explosive enables it to flatten out and make excellent contact with the target, so that the resulting damage is much greater than with an equal weight of a solid explosive.

ALUMINIZED EXPLOSIVES

At the present time, there are four aluminized explosives in military use: Tritonal, which is aluminized TNT; Minol, which is aluminized Amatol; Torpex, which is aluminized Composition B, with the addition of a little extra TNT; and Torpex D-1 or HBX, which is Torpex containing 5% desensitizer.

1. *Torpex.*

This explosive contains RDX, TNT, powdered aluminum and a trace of wax. Several compositions have been used at various times, but the material in general use at the present time contains 42% RDX, 40% TNT, and 18% of Aluminum. As an explosive for producing high velocity fragments, air blast and underwater shock waves, this is the most powerful explosive in use today. As a bomb filling, it produces an area of blast damage somewhat more than 60% greater than the same volume of TNT, and about 30% greater than the same volume of Composition B. The chemical stability of Torpex is excellent if water is excluded. In the presence of water, gas is given off. However, if the ingredients are thoroughly dried, there is no difficulty, since Torpex is not hydroscopic. The disadvantage of Torpex is that it is a somewhat shock- and bullet-sensitive material. It is used as a filler for depth bombs and torpedo warheads, since under water it is equivalent in damaging power to a 50% greater weight of TNT. The sensitivity of Torpex is probably too great to make its use feasible in aerial bombs, at least of the G. P. type, where the explosive may have to withstand a drop on a hard surface without detonating. (See following section on HBX.)

2. *Minol.*

The composition in present use by the British contains 40% TNT, 40% ammonium nitrate and 20% aluminum. This is a powerful explosive for air blast and under water applications, although inferior to Torpex. It gives an area of blast damage about 40% greater than the same volume of TNT. Care must be exercised in handling this explosive, since it is hydroscopic, and in the presence of water, reaction with the aluminum takes place and gas is given off. Minol has been extensively used by the British as a filling for high-capacity bombs, but is probably too sensitive for use in G. P. bombs.

3. *Tritonal.*

The present composition is 80% TNT and 20% aluminum, but there is evidence that a 70/30 composition is more powerful. This explosive is somewhat inferior to Minol, both for air blast and underwater damage, but is still quite powerful. It gives an area of blast damage about 35% greater than the same volume of TNT. It had been loaded in this country for use by the British for some months, and has recently been adopted for loading into G. P. bombs by our own Ordnance Department. It might be pointed out that Tritonal gives about 10% greater area of blast damage than Composition B. While somewhat more sensitive than TNT, tests indicate that it is sufficiently insensitive for use in aerial bombs (except A. P. bombs). Planes will be 35% more effective in carrying Tritonal-loaded bombs than in carrying TNT-loaded bombs. The information on the fragmentation effectiveness of Tritonal is meager, but in this respect it is probably at least equivalent to TNT and perhaps better.

4. *Torpex D-1 or HBX.*

This explosive is Torpex to which has been added 5% of a desensitizer which consists mostly of wax. The addition of inert material decreases its performance slightly below that of Torpex, but it is nevertheless more effective than any other available filling for blast and underwater damage. Tests conducted to date indicate that while it is somewhat more sensitive than TNT, it is sufficiently insensitive for use in depth bombs, aerial mines, G. P. bombs, etc. It is understood that the U. S. Navy is in the process of converting most of its loading from Torpex and TNT to HBX. It might be mentioned that the 12,000-lb so-called earthquake bombs are being loaded with this explosive and have been performing very well.

LIQUID EXPLOSIVES

Up to the present time, liquid explosives have been very little used, because for most applications they have no particular advantages over solid explosives and many disadvantages. Because of the fact that they can leak out of containers so readily they have not normally been considered for use as bomb or shell fillings. As a result, the information available on liquid explosives is less extensive than that on solid explosives. Nitroglycerine, which is a liquid, is of course manufactured on a very large scale because of the low price at which it can be sold. However, it is almost never used in the liquid state. It is the most important constituent of various types of dynamite, and is also combined with nitrocellulose to form double-base smokeless powder. In general, one can say that the only liquid explosive about which we know very much is nitroglycerine, and it is much too touchy a material to be very attractive for use in the pure state. Nitroglycerine can be desensitized by the addition of various materials, and some work has been done along this line. However, while such products are much safer to handle than pure nitroglycerine, it seems to be true that liquid explosives made by desensitizing nitroglycerine are more hazardous to handle than solid explosives of comparable power.

Most of the other liquid explosives which have been investigated consist of mixtures of a fuel with an oxidizing agent, neither one being an explosive alone. One such mixture is Dithekite, which has been studied by the British. It consists of a mixture of nitric acid and nitrobenzene, with about 10-13% of water. This material is fairly insensitive toward shock, but is very corrosive due to its nitric acid content. Its power is about the same as that of TNT. A somewhat similar mixture, Anilite, has been studied by the French. This contains benzene or nitrobenzene and nitrogen tetroxide, and arrangements are usually made to mix the two constituents at the last minute. It is obviously not a very pleasant material.

If, at the present time, one desires to use a liquid explosive in large quantities, one is more or less restricted to one based on nitroglycerine, or on a mixture of a fuel and an oxidizing agent, such as nitric acid, because of considerations of supply. However, there are a number of other possibilities which may be made available in the future if they prove to be useful. One such compound is nitromethane. This compound is now made commercially, but not in sufficient quantities for large scale uses. However, there is no reason why facilities could not be developed for its production, since it is made from hydrocarbons and nitric acid. While nitromethane has not been extensively studied, it appears to be a stable compound, not unduly sensitive to mechanical shock, and considerably more powerful than TNT on a weight basis. On a volume basis the comparison is less favorable, since a good TNT casting will have a density of around 1.55 gm/cc, whereas the density of nitromethane is only 1.13 gm/cc.

Another liquid oxidizing agent, which may be available in the future, is hydrogen peroxide. A mixture of this compound with a fuel, ethyl alcohol for example, should be a rather powerful explosive, based on energy content. However, little information is available in this country concerning its behavior and properties.

In general, it does not appear probable that any liquid explosives will be developed which will be appreciably more powerful than present solid explosives. However, for applications in which a liquid is definitely desired because of its physical state, liquid explosives may have considerable use in the future. As yet, the field has not been well studied.

QUANTITATIVE COMPARISONS

While thermal data are available for the various materials in use or contemplated use as high explosives, there is no simple method for making reliable computation of the power of an explosive from these data. Indeed, since, as was pointed out previously, the relative effectiveness of an explosive depends on the use to which it is put, it is obvious that no single quantity, either computed or experimental, can give a unviersal measure of the performance of an explosive. Even if the consideration is restricted to a single type of action, predictions on the basis of thermal data are only approximate. It has long been customary to use both the heat of detonation and the characteristic product (heat of detonation times volume of gas produced) as measures of some sort of effectiveness. In general, it is found that there is at least a qualitative correlation between either of these quantities and, for example, the blast impulse for unit weight of explosive.

When an explosive detonates and creates a blast wave, the hot, compressed gases expand, doing work on the atmosphere until the pressure of the explosion gases has fallen to a value of the order of one atmosphere. The amount of work done during such an expansion can be calculated, if the heat quantities for the explosive are known, and some assumptions are made concerning the equation of the state of the product gases during the high pressure stages of the expansion. When such calculations are made for the common high explosives, it is found that after expanding to one atmosphere, the temperature of the product gases is not far from room temperature. From the laws of conservation of energy, it follows that the work of expansion is equal (approximately) to the energy released on detonation, if the latter is defined as the difference between the energy of the product gases and energy of original explosive, both at normal temperature and pressure. On this basis, one would expect to find a correlation between blast effectiveness of an explosive and its heat of detonation. Empirically, it appears to be approximately true that the blast impulse is proportional to the square root of the heat of detonation. For explosives which have a very high detonation temperature, the explosion products will usually be at a temperature appreciably above room temperature after expansion, and here the conversion of heat into useful work is not complete. Explosives containing appreciable amounts of aluminum behave in this way, and for these explosives, the value of the heat of detonation somewhat over-estimates the magnitude of the blast impulse.

The SBX explosives form a class by themselves. The real explosive here is a mixture of a fuel, which is actually carried to the target, with air. Obviously, the volume occupied by unit weight of such an air-fuel mixture is very large compared to that occupied by the same weight of conventional high explosive. As a result, the maximum pressure produced when detonation occurs is very much lower for SBX than for a conventional high explosive. Actually, the maximum detonation pressure in the former case will be of the order of 10 or 20 atm, whereas for a high explosive it is of the order of 200,000 atm. If we now compute the adiabatic for the explosion products of gasoline and air, for example, we find that about half the total energy of the seaction is retained by the explosion products, and consequently, the useful work is only half the heat of detonation. This is due, of course, to the small expansion ratio involved.

There is some uncertainty in the calculated value of the heat of detonation for many high explosives. This is due to uncertainty as to exactly what the composition of the products is. Many explosives contain insufficient oxygen for complete conversion of the carbon and hydrogen to carbon dioxide and water, and, in fact, there is often not enough oxygen to convert the carbon and hydrogen to carbon monoxide and water. In this latter case, there is doubt as to the way in which the oxygen is divided between the hydrogen and the carbon. While the equilibria involved have been studied at ordinary pressures, they are not known for pressures of the order of 100,000 atm. Indeed, the composition of the products undoubtedly depends on the conditions under which the explosive is used. This uncertainty is especially pronounced in the case of TNT, since in this compound there are only six atoms of oxygen for reaction with five atoms of hydrogen and seven atoms of carbon.

In Table I, the heats of detonation have been calculated, in general, on the assumption that all of the hydrogen is converted to water, and what oxygen remains reacts with the carbon. This procedure tends to overestimate the heat of detonation, but underestimates the volume of gas produced in the detonation. The value of the characteristics product (heat by volume of gas) is not very sensitive to changes in assumptions concerning the composition of the products, since there is this compensation.

In Table I, many of the quantities have been tabulated both for unit weight and for unit volume of the explosive. Depending on the application, one or the other quantity may form the best basis for comparing different explosives.

In Table II, some of the important quantities are tabulated for various SBX explosives. The heats of detonation have been calculated for the reaction of the fuel with an amount of air sufficient to give complete conversion of the carbon and hydrogen to carbon dioxide and water. For SBX, it seems evident that the characteristic product has little meaning and the available heat, or available work, forms the best basis for estimating the potential performance of this type of explosive, relative to conventional H.E. As was pointed out in a previous section, SBX explosives have been found effective in confined spaces but ineffective when exploded in the open. However, it is entirely possible that ways will be found to make the explosion of SBX take place fast enough to be effective in the open.

It is interesting to note that on a volume basis, gasoline is potentially a very effective fuel for SBX. Any other hydrocarbon would give about the same figure. On a weight basis, however, hydrogen is rather in a class by itself.

TABLE I

Explosive	Loading Density (1)	Heat of Detonation, cal/gm (2)	Volume of Gas, N. T. P., cc/gm (3)	Character-istic Product, $\frac{\text{cal x cc}}{\text{gm}^2}$ x 10^{-6} (4)	Estimated Efficiency (5)	Available Heat, cal/gm (6)	Available Heat, cal/cc (7)	Available Heat, cal/cc$^{1/2}$ (8)	Relative Available Heat, cal/cc Comp. B = 100 (9)	Relative Blast Impulse, Comp. B = 100 (10) (On volume basis)	Relative Damage Area, Comp. B = 100 (11) (On volume basis)
TNT..............................	1.55	1000	740	0.74	100%	1000	1550	39.4	85	91	83
Amatol 60/40......................	1.55	865	940	0.81	104%	900	1395	37.4	74	80	64
Tetryl............................	1.55	1050	820	0.86	100%	1050	1630	40.4	89	—	—
Composition B.....................	1.64	1110	850	0.94	100%	1110	1820	42.6	100	100	100
Pentolite.........................	1.60	1010	866	0.87	100%	1010	1615	40.1	89	—	—
Torpex............................	1.74	1630	740	1.21	94%	1530	2260	51.6	146	114	130
Tritonal..........................	1.70	1580	570	0.90	87%	1315	2340	48.4	129	105	110
Minol.............................	1.70	1440	771	1.11	97%	1400	2380	48.8	131	107	114
Nitroglycerine....................	1.60	1510	567	0.86	93%	1405	2250	47.5	124	—	—
Nitromethane......................	1.13	1205	920	1.11	100%	1205	1360	36.9	75	—	—
Hydrogen Peroxide + Ethyl Alcohol*.	1.28	1375	945	1.30	100%	1375	1760	42.0	97	—	—
Gasoline + Liquid Oxygen*..........	1.0	2540	742	1.88	100%	2540	2540	50.4	140	—	—
Liquid Hydrogen + Solid Oxygen*...	0.46	3170	1246	3.95	100%	3170	1460	38.2	80	—	—
Solid Acetylene + Liquid Oxygen*....	1.0	2940	635	1.87	100%	2940	2940	54.2	162	—	—

* Mixture balanced so as to give carbon dioxide and water. (See following page for notes on Table I.)

NOTES ON TABLE I:

1. The efficiency is given as the percentage of the heat of detonation which is converted to work, i.e.,

$$= \frac{\text{Available Heat}}{\text{Heat of Detonation}} \text{ x } 100$$

2. The figures in 2-9 are computed from the heat of combustion of the explosive. The figures in column 10 are obtained from the measurements on bombs. The figures in column 11 were obtained by squaring the values in column 10 and dividing by 100.

TABLE II: VARIOUS FUELS AS SBX

Fuel	Assumed Loading Density	Heat of Detonation, cal/gm	Heat of Detonation, cal/cc	Estimated Efficiency	Available Heat per gm	Available Heat per cc	Available Heat per $cc^{1/2}$	Relative Available Heat per cc, Comp. B = 100
Aluminum	1.2	3,820	4,590	30%	1,150	1,375	37.0	76
Gasoline (C_8H_{18})	0.70	11,430	8,010	50%	5,720	4,000	63.4	220
Acetylene (solid)	0.73	12,000	8,750	45%	5,400	3,940	62.9	217
Hydrogen (liquid)	0.08	29,000	2,320	50%	14,500	1,160	34.2	64
Composition B *	1.64	1,110	1,820	100%	1,110	1,820	42.6	100

* The figures for Composition B refer to its action as a conventional high explosive, not as SBX, that is, no reaction with oxygen of the air is assumed. *The figures are included in this table merely for comparison.*

NOTES ON TABLE II:

1. In computing heat of explosion per gram and per cubic centimeter, the weight and volume of the *actual fuel only* are *considered, not those* of the air involved in the reaction.

2. The available heat is heat of detonation multiplied by the estimated efficiency. For SBX, usually less than half of the total heat is converted into work.

PART III

TERMINAL BALLISTICS AND DESTRUCTIVE EFFECTS

By

N. M. NEWMARK

PART III

TERMINAL BALLISTICS AND DESTRUCTIVE EFFECTS

23 NOVEMBER 1945

SUMMARY

This report is a discussion of the present state of knowledge regarding the means of damaging or destroying given targets with airborne weapons of the high-explosive or incendiary type. Basic physical principles governing target vulnerability are described, and their application to the problem of weapons selection is considered. There are still many major uncertainties about the actual effectiveness of bombs under operational conditions in spite of the experience gained in the war. With the advent of new weapons, such as the atomic bomb, much of the specific data accumulated during recent operations has become outmoded. However, many of the fundamental principles of the relatively new science of terminal ballistics are stilll valid and will remain useful as a basis for choice of means of destruction should the need ever again arise. Means of improving the effectiveness of ordinary high-explosive weapons are discussed, and recommendations are made for specific improvements and developments in these weapons.

MEANS OF PRODUCING DAMAGE

Whatever the type of weapon considered and whatever the nature of the target attacked, damage can be produced by one or more of the physical phenomena associated with the bringing to rest of a missile, with the detonation of an explosive, or with chemical or bacteriological action. It is convenient to consider these phenomena under the following categories:

(1) Impact, including penetration into or perforation through an object. The damage produced may be purely local cratering or rupture, or it may be more extensive due to transfer of shock waves through the structure.

(2) Fragmentation, which is essentially impact of small particles, usually from the case of a bomb, rocket, or shell.

(3) Blast in air, arising from the detonation of an explosive, or the sudden release of large amounts of energy.

(4) Blast in earth or water. The shock wave from the detonation is transmitted with greater vigor through these denser media, often with considerably greater effect on a target than the shock wave from detonation in air.

(5) Debris, set in motion at relatively high velocities almost as fragments; also the debris resulting from destruction of part of a structure may help to damage the remainder.

(6) Heat, in the flame front of the blast, or radiant heat.

(7) Fire, which may result from the effects of an explosive, or may be induced by special incendiary weapons.

(8) Chemical action, such as smoke, poison gas, and the like.

(9) Bacteriological action.

There are weapons available which depend for their effect on one or the other of these phenomena, sometimes on a combination of several of them. There are targets that are particularly vulnerable to one or more of these causes of damage, offering much greater resistance to the others. Consequently some weapons have a considerably greater effect on particular targets than on others. The proper choice of weapons requires a matching of the vulnerability of the target with the capabilities of the weapon.

BASIC PHYSICAL PRINCIPLES

IMPACT AND PENETRATION

Although there has been extensive study of the problem of penetration of bombs and projectiles into earth, concrete and steel, most of the information is empirical. That is, from extensive trials with particular weapons, it is possible to predict what such weapons will do when they strike objects of the same type as those for which the data have already been determined. But the laws governing the phenomena of penetration are not yet adequately understood and it is impossible to predict what some new design of projectile or bomb will do under conditions considerably different from those which have been studied. There is a major lack of information on the effect of the impact on the projectile or bomb itself. This becomes of prime importance when questions arise of breakup of cases or shatter. Penetration and perforation depend on the following:

(1) Geometric properties of the missile; weight, diameter, shape, wall thickness.

(2) Physical properties of the missile; strength of the material, ductility, hardness.

(3) Geometric properties of the target; dimensions, manner of support.

(4) Physical properties of the target; strength, hardness, homogeneity.

(5) Striking conditions; velocity, angle of incidence.

In general, other things being equal, penetration into earth will be on the order of from 5 to 10 times the penetration into concrete, which in turn will be from about 10 to 20 times the penetration into steel.

The estimated penetration of several typical bombs into earth, concrete, and steel is shown in Fig. 1. The data were taken from studies made by Division 2 of NDRC. In general, the penetration is greater for bombs dropped from high altitudes because of the greater velocity and the more nearly normal incidence of the bomb at impact. The maximum penetration in earth that might be reached with an inert bomb may not be reached with a bomb fitted with a short delay fuse because the bomb may detonate before its motion is stopped. The path of a bomb in a resisting medium such as earth is shaped very much like the letter J. The bomb tends to yaw, or turn sideways, and in most instances may turn and lie parallel to the surface, or even point upward, by the time it comes to rest.

The deceleration of a bomb penetrating concrete is much more rapid than in earth and the forces acting on the bomb casing are therefore considerably larger. Thin-cased bombs will burst open and the explosive charge may deflagrate upon striking concrete. Even general-purpose bombs may not survive the impact without breakup of the case or premature detonation. A bomb will perforate a considerably greater thickness of concrete slab than the distance it is likely to penetrate into massive concrete. The shock wave from the impact tends to cause a scabbing or spalling of the back face of the slab ahead of the path of the bomb. Even when the slab is too thick to be completely perforated, a fairly large scab may still be formed, and the velocity of the concrete fragments may do considerable damage to the interior of a structure that has been hit.

In Fig. 1 the values indicated for perforation of steel are the thickness of plate which the bomb is capable of defeating without serious damage to the bomb case. For greater thickness of plate, the case may break up before the bomb has penetrated into the plate.

FRAGMENTATION

A pictorial representation of the way in which a cased explosive produces fragmentation of the casing upon detonation of the explosive is shown in Fig. 2. The fragments produced when the pressure generated by detonation of the charge inside a bomb or shell bursts the case, behave as projectiles of irregular size and shape. The fragments may damage a structure or produce casualties to personnel by the force of their impact or by penetration into or perforation through the object they strike. The properties of fragments, including their initial velocity, general shape, and mass, and the range-velocity relation for individual fragments, have been studied extensively by the Ordnance Department as well as by others. Data are available for the average number of penetrations through particular thicknesses of material at given distances from selected bombs and shells. Although these physical data are reasonably well known, there is very little evidence concerning the relation between number of pene-

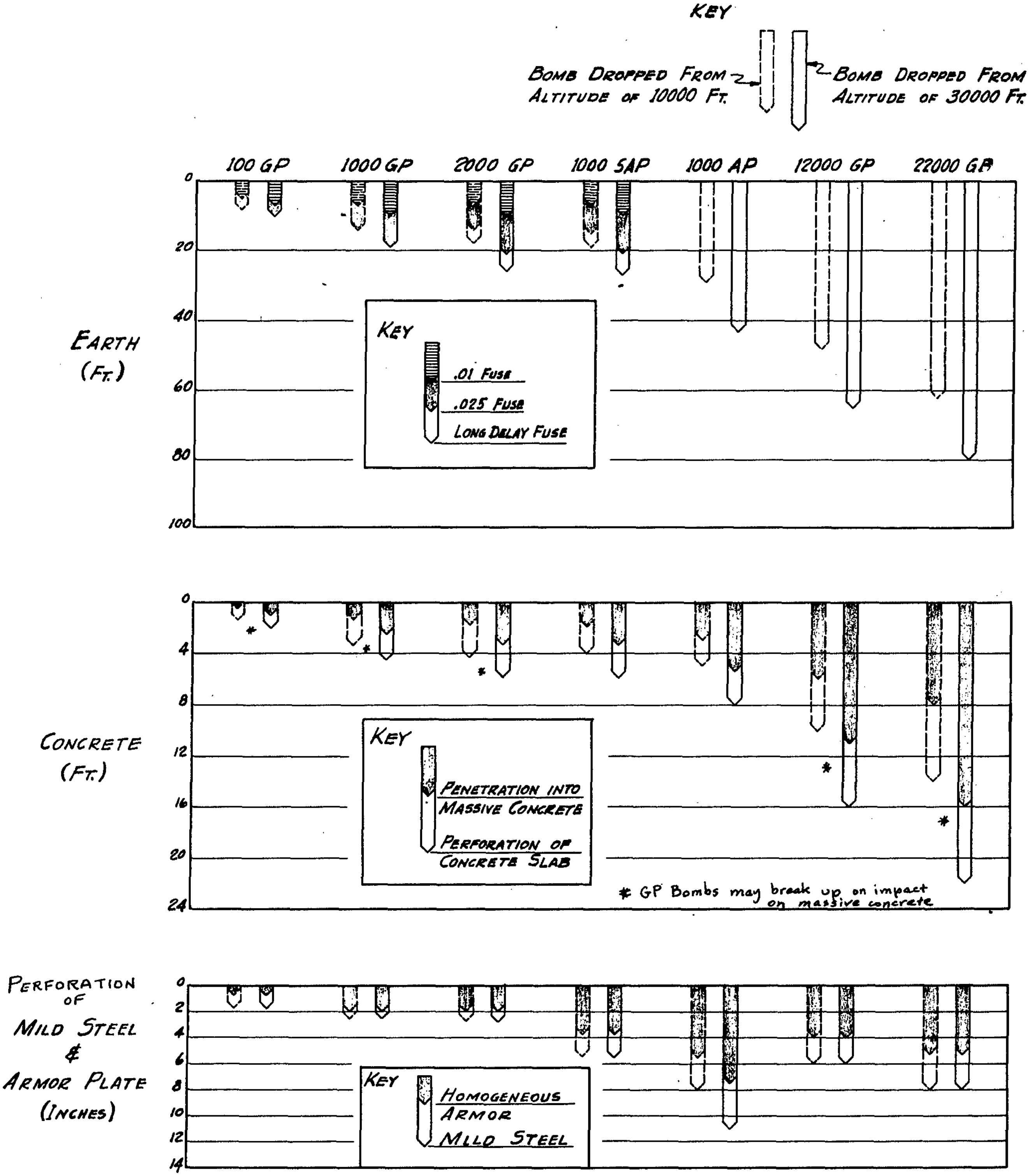
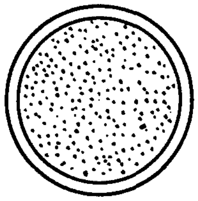
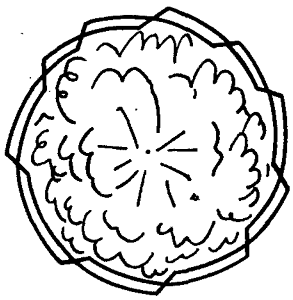


Figure 1 — Penetration of Typical Bombs in Earth, Concrete, and Steel

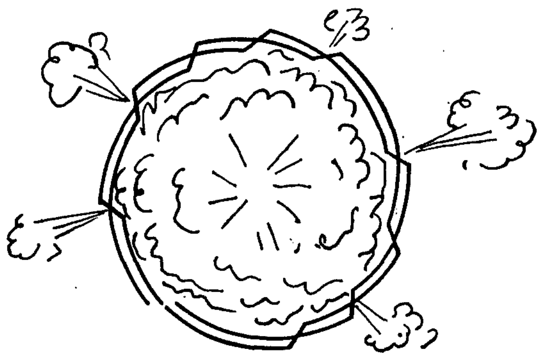


1 BOMB CASE FILLED WITH EXPLOSIVE PRIOR TO DETONATION

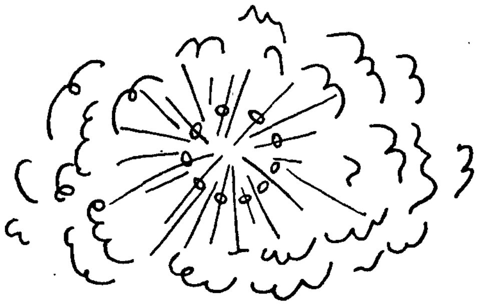
2 IMMEDIATELY UPON DETONATION, CASE EXPANDS TO ABOUT $1\frac{1}{2}$ ORIGINAL DIAMETER. SHEAR CRACKS DEVELOP



3 FAILURE OF CASE IN SHEAR PROGRESSES TO GIVE 45°-EDGED FRAGMENTS



4 JUST PRIOR TO BREAK-UP OF CASE, EXPANDING GASES START TO ESCAPE THROUGH FAILURE CRACKS



5 AS CASE BREAKS UP, FRAGMENTS ARE IMPELLED OUTWARD BY THE OUTWARD-MOVING GASES

Figure 2 — Rupture and Fragmentation of Bomb Case

trations of a structure and actual degree of damage to the structure; that is, one cannot say with any assurance that a given number of penetrations per square foot will result in a given probability of damage of a particular degree.

In general, the greater the thickness of material, the larger the fragments that are required to damage it. Fragmentation is primarily effective in producing casualties to personnel and in damaging or destroying structures made up of material thin enough to be perforated by the fragments. Such structures are airplanes, trucks, and light machines. In order to be effective, fragmentation must take place in the air since earth and water offer so much more resistance to the travel of fragments. The direction of travel of the major part of the fragments from a missile depends on the shape of the case, on the location of the charge, and on the manner of initiation. For most missiles, fragmentation would be greater in effectiveness if the detonation were initiated by means of a tail fuse while the missile was still some distance above the target and traveling toward it. The zone of most intense fragmentation around a missile is generally lateral.

It is possible by various expedients to control the fragments both in size and in direction. Experimentation has been conducted with controlled fragmentation. The most successful results to date have been with wire winding around a thin case, as in U.S. fragmentation bombs. Other developments that appear promising are the formation of fragments of predetermined size by shaping the charge with paper liners so as to cut the case with the so-called Munro effect, the shaping of the bomb case so as to direct the spray of fragments into a more intense forward zone, and the use of material for fragmentation-bomb cases with more favorable properties.

BLAST IN AIR

When an explosive detonates, a shock wave is set up in the air surrounding the explosive and travels outward. The shock wave as it passes a particular point is characterized by an almost instantaneous rise in pressure. Then the pressure falls off fairly uniformly from this peak pressure until it reaches zero. The pressure phase of the shock wave or blast wave is followed by a suction phase in which the pressure falls below atmospheric. After a time somewhat longer than the duration of the pressure phase, the pressure returns to normal. Typical time-pressure curves at various distances from a 2000-lb GP bomb are shown in Fig. 3. The pressures shown are the "side-on" pressures. It may be seen that the peak pressure decreases rapidly as the distance from the bomb increases, and the duration of the pressure and suction phases of the blast increase slightly with distance. The velocity of propagation of the blast wave is several thousand feet per second near the detonation but falls rapidly and approaches the velocity of sound, about 1100 ft/sec, at great distances from the detonation.

The maximum positive impulse that can be given to an object by the blast wave is measured by the area under the pressure-time curve during the pressure phase. The magnitude of the pressure and the impulse vary with the weight of explosive, the type of explosive, the weight of the case in which it is placed, the distance from the detonation, and the relative direction of the surface which is exposed to the blast. In general the pressure "face-on" to the blast is at least twice as great as the pressure "side-on."

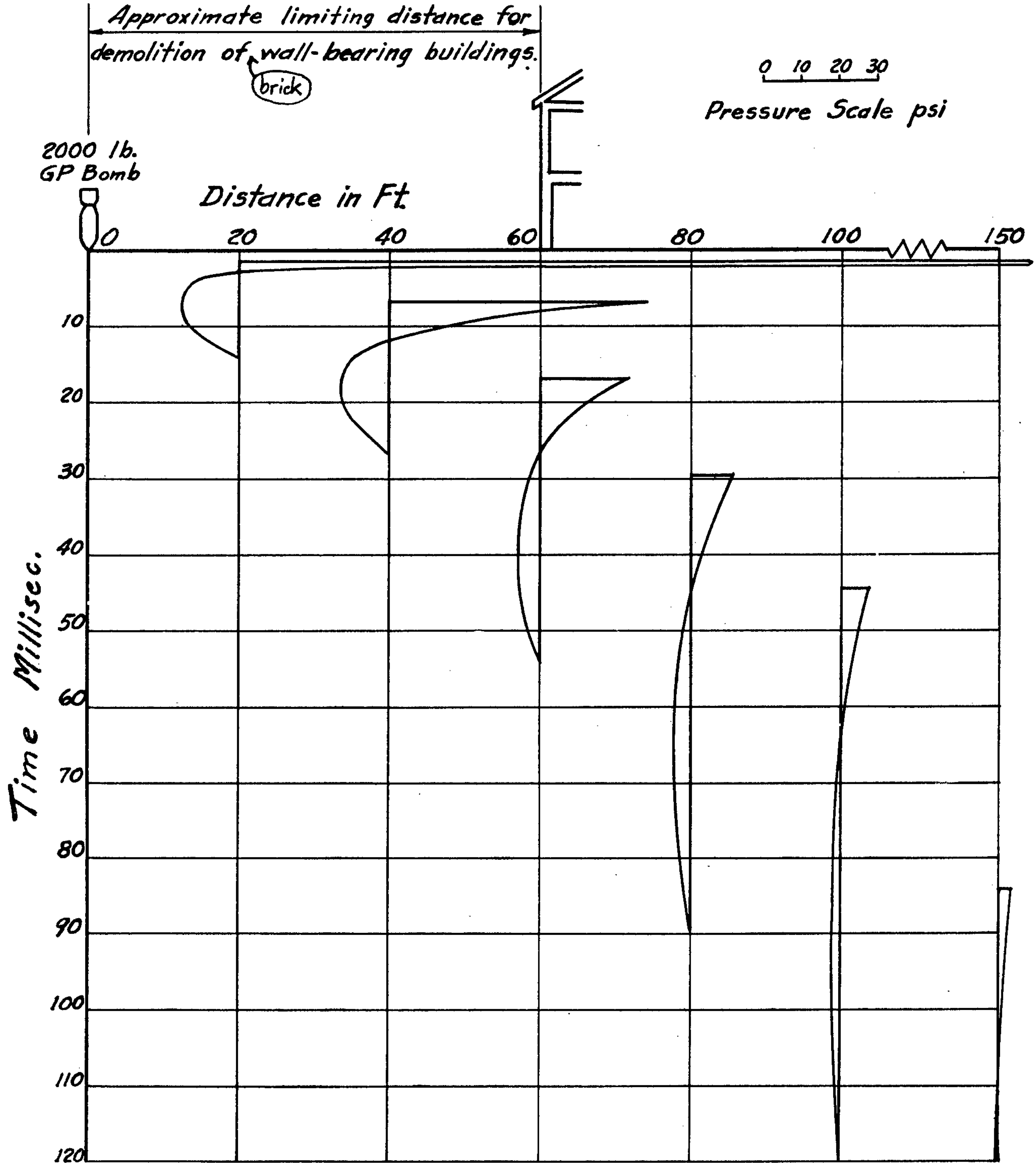


Figure 3 — Time-Pressure Relations at Various Distances for a 2000-lb General Purpose Bomb

As an example, the peak pressure 50 ft away from the detonation of a 500-lb GP bomb is about 12 lb/sq/in., and the positive impulse about 0.06 lb/sec/sq in. The duration of the positive phase is about 0.01 sec. The duration is much less for distances closer to the bomb and is somewhat greater for distances further from the bomb. For the conditions considered in this illustration, the time interval between the detonation and the peak positive pressure at the point considered is perhaps from 0.02 to 0.03 sec. For somewhat greater distances, the shock wave moves with the velocity of sound in air. The pressures and impulses quoted herein are all for "side-on" conditions. They would be approximately doubled for "face-on" exposure.

In general, for all other conditions similar, the magnitude of the peak pressure at a given distance r from a weight of explosive W is a function only of the quantity $\frac{W^{1/3}}{r}$, whereas the duration of the positive phase for the same peak pressure increases in direct proportion with $W^{1/3}$. Consequently, the peak pressures will be equal at distances in the proportion of 1:2 for weights of explosive in the proportion of 1:8. The durations of the positive pressures will be in proportion of 1:2 and consequently the positive impulses will be in the proportion of 1:2 at the corresponding distances. In general, the positive impulse is very nearly a linear function of $\frac{W^{2/3}}{r}$.

When the blast wave reaches a structure, the parts of the structure are set in motion by the impulse from the blast. The momentum given to the structure is equal to the impulse absorbed by the structure. The resistance that the parts of the structure offer to the motion sets up forces within the structure which attempt to bring it to rest. These forces may be great enough to produce damage or collapse of the structure or of some of its parts. When the duration of the pressure phase of the blast wave is small compared with the fundamental period of elastic natural vibration of the structure; or for a plastic resistance of the structure, if the duration is small compared with the time required for the structure to reach its limiting deflection, the impulse absorbed will generally be equal to the total impulse available. If, however, the duration of the pressure phase is long compared with the fundamental period of the structure, or with the time required for the structure to reach its limiting deflection, the impulse absorbed by the structure may be considerably less than that available in the blast wave. In the former case, the quantity which determines the amount of deformation of the structure is the positive impulse. In the latter case, and in general for stiff, relatively brittle structures, the peak pressure is the quantity which determines the resistance of the structure.

When impulse is the quantity of fundamental importance, the area vulnerable to damage from the bomb increases as $W^{4/3}$ which means that the area increases more rapidly than the weight of the charge and it is, therefore, an advantage to use large bombs. When peak pressure is the quantity of importance, the area vulnerable to damage increases only as $W^{2/3}$ and it is, therefore, an advantage to use small bombs, provided they are large enough to do the required amount of damage. It should be pointed out, however, that as the weight of charge increases, the peak pressure corresponding to a given impulse becomes smaller and the duration of the pressure phase becomes longer. The peak pressure may even become equal to or only slightly greater

Rigid bldg [illegible] I [illegible] 90 ms/in²
Heavy I - 120-150 lb/in²

than the plastic resistance of the structure. Therefore the impulse criterion does not hold indefinitely as the charge weight increases, and the increase in area with weight of bomb does not go up indefinitely. There is some optimum size of bomb for structures that can be damaged by blast.

Rough estimates of the distance from detonations at ground level of large bombs at which brick wall-bearing buildings will be demolished are as follows: for the 2000-lb GP bomb from about 55 to 60 ft; for the 4000-lb light-case bomb, about 110 ft; for the 12,000-lb GP bomb (equivalent to the British "Tallboy"), about 120 ft (this bomb has a heavier case and only about 40% more explosive charge than the 4000-lb LC bomb); and for the 22,000-lb GP bomb (equivalent to the British "Grand Slam"), about 150 ft. Of course, demolition may occur in some instances at considerably greater distances, and relatively mild damage may be found at much smaller distances. In general, a more effective measure of the efficacy of a particular bomb against a particular type of construction is given by the so-called "mean area of effectiveness," which is defined in terms of probability of a given degree of damage, and is usually expressed in acres or square feet per ton of bomb.

As a result of experience gathered from the effect of German bombs and from the assessment of the results of their own raids, the British arrived at rough rules to determine the effectiveness of bombs. These rules may be summarized in the following way: The distances at which light structures and wall-bearing brick buildings will suffer demolition correspond to the distances at which the side-on impulse is about 90 lb-millisec/sq in. For heavy construction, the critical impulse is from about 120 to 150 lb-millisec/sq in. For damage visible on reconnaissance photographs, the critical values of impulse are respectively from about 60 and 80 lb-millisec/sq in.

Both peak pressure and positive impulse for a given charge weight are increased at the ground level when the detonation takes place in the air some distance above ground. The increase arises from the complicated reflection of the shock wave from the ground at relatively small angles of incidence. Theoretical calculations indicate that the area over which a given impulse exists may be increased as much as from 50 to 100% by the proper height of air burst. In general the height should be of the order of from about 40 to 50% of the radius at which the particular impulse desired is found. The theoretical studies also indicate that the optimum size of blast bomb is increased by air burst.

The impulse from a cased charge is less than for an uncased charge of the same weight. For example, the impulse at a given distance due to the charge in a GP bomb is from about 30 to 50% less than the impulse due to the same weight of bare charge. Consequently, for maximum blast effect it is desirable to use as light a case as possible.

BLAST IN EARTH OR WATER

The shock wave transmitted through earth or water has a greater peak pressure and a greater impulse than the shock wave from the same explosive in air. Also the negative phase of the blast wave does not exist. Consequently, damage may be greater for a structure surrounded by earth or water when a bomb bursts in the surrounding medium compared with the damage when the bomb bursts in air. The estimated effect of some typical large bombs on reinforced concrete walls is shown in Fig. 4.

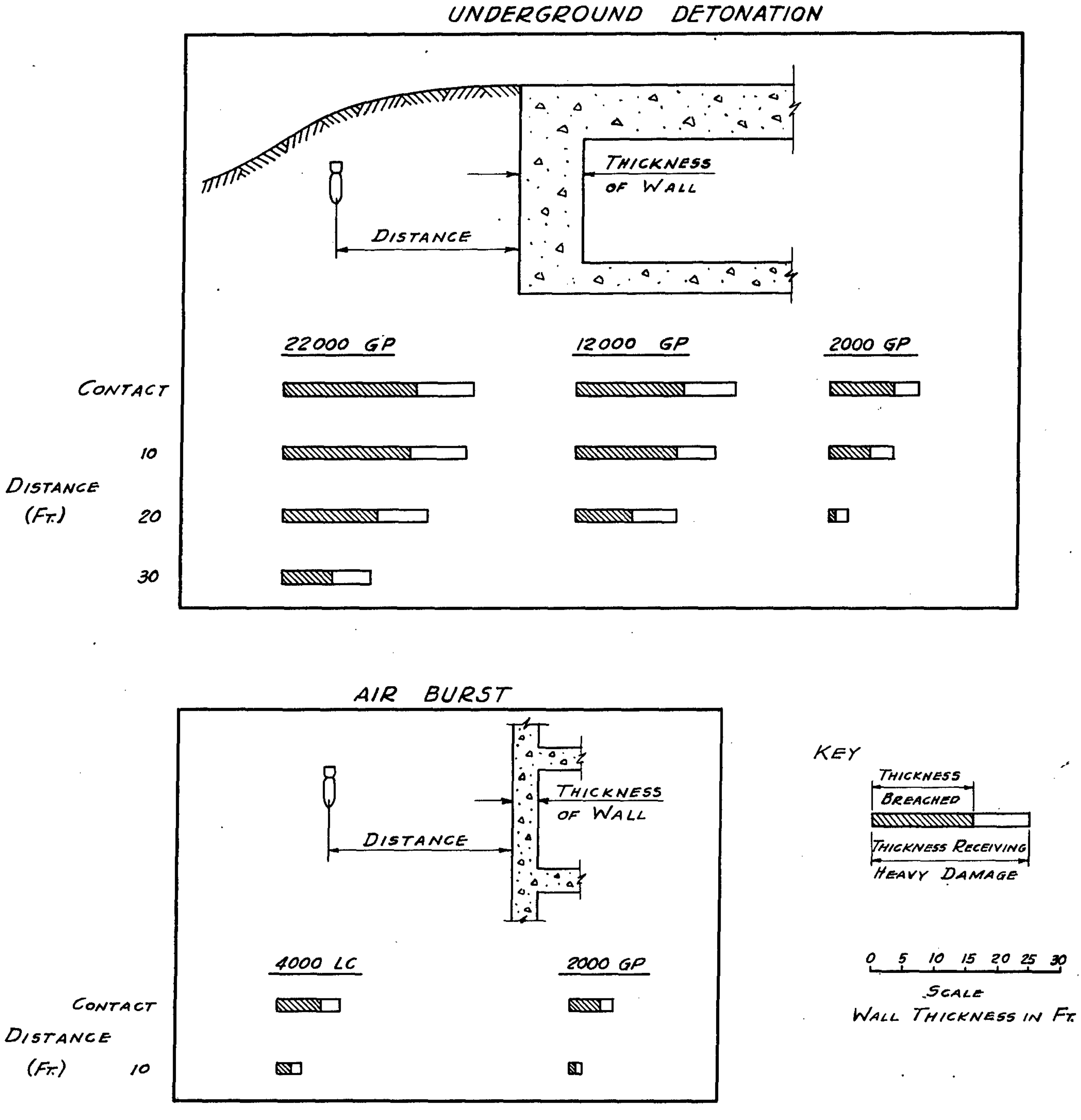


Figure 4 — Damage to Reinforced Concrete Walls from Detonation of Bombs Underground or in Air

For underground detonation, the thicknesses of walls breached and heavily damaged is indicated for several distances of the bombs from the wall. The same information is indicated for burst in air of 2000-lb GP and 4000-lb LC bombs. The only direct comparison of underground and air burst effects is for the 2000-lb GP bomb. The thickness of wall demolished is several times greater for underground explosion. Comparison of the figures with the penetration to be expected on impact against concrete leads to the conclusion that in many cases more serious damage can be done to a concrete fortification by a near miss than by a direct hit.

The fundamental relations regarding peak pressure and impulse have the same scale effects in either earth or water as in air and the same general conclusions apply. In addition, for structures surrounded by or supported by earth, damage may be obtained when the movement of the earth is great enough to throw the structure out of line by disturbing its supports; damage may also be caused by undermining of the structure when the crater produced by the detonation removes some of the material supporting the structure.

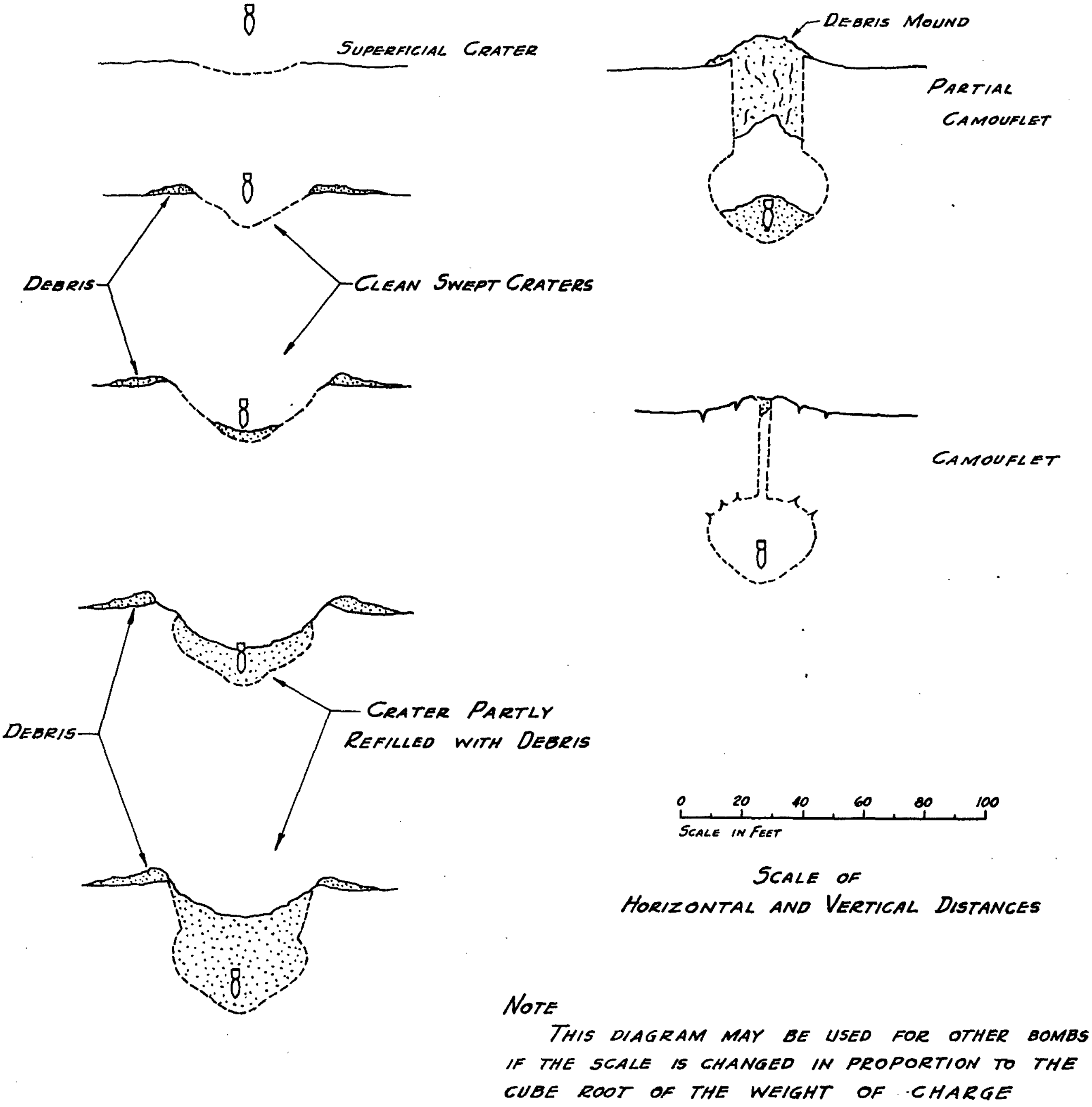
Typical craters in clay soil due to the detonation of a 2000-lb GP bomb at various depths beneath the surface are shown in Fig. 5. The same sketches can be used for other bombs provided that depth and crater dimensions are changed approximately in proportion to the cube root of the charge weight. That is, if a 2000-lb bomb having about 1100-lb charge produces a crater of diameter 53 ft when detonated at a depth of 10 ft, a 12,000-lb bomb having a charge weight of 5000 lb will produce a crater of diameter 88 ft when detonated at a depth of 16.5 ft.

DEBRIS

Damage may be caused to relatively light structures from detonation in earth on rock when the material displaced from the crater moves with high enough velocity to produce fragmentation effects on the structure. Damage can be caused to personnel in this way also. Damage from debris can also be obtained in a multistory building when destruction is produced in the upper floors. The accumulated debris may fall on lower floors, overloading them and causing continued destruction.

FIRE, CHEMICAL ACTION, ETC.

Structures to be damaged by these means must be particularly vulnerable to the means of attack. Countermeasures may be applied to prevent or to reduce damage from fire or chemical action. The quantity of munitions needed to produce damage is influenced by the active and the passive countermeasures which may be used by the enemy. For example, when incendiary bombs are used, the total quantity of incendiaries and the density per unit area on the target must be great enough to overload the fire-fighting facilities. Combination of fire-fighting munitions with other weapons to discourage fire fighting has been attempted, and seems to offer possibilities of advantage.



NOTE

THIS DIAGRAM MAY BE USED FOR OTHER BOMBS IF THE SCALE IS CHANGED IN PROPORTION TO THE CUBE ROOT OF THE WEIGHT OF CHARGE

Figure 5 — Typical Craters and Camouflets in Clay for 2000-lb GP Bomb

CLASSIFICATION OF TARGETS

Targets may be classified in several ways, the most fruitful of which depend on the nature of their resistance to attack and on the operational means required to make the attack. We may distinguish broadly between "strategic" targets and "tactical" targets, whereby strategic targets we mean those installations where the enemy produces the means for waging war or for supporting his population, and by tactical targets we mean military installations which are directly connected with his armed forces and military efforts.

For purposes of choosing weapons for attack, a classification of targets according to the mechanism of their resistance is probably most important. The following classifications appear reasonable:

(1) Personnel.

(2) Structures subjected to major damage from blast. This includes light industrial buildings, wall-bearing buildings, residential areas, and many parts of special industrial installations.

(3) Very heavy structures offering great resistance to blast. These include heavy industrial structures, warehouses, multistory steel and concrete frame buildings, bridges, and parts of many other targets.

(4) Targets subjected to damage by fire. This may include storage facilities for fuel and ammunition, as well as industrial buildings, oil refineries, and residential areas.

(5) Targets subjected to damage by cratering, such as airfields, highways, and railroads.

(6) Targets particularly vulnerable to fragmentation including vehicles, thin-walled construction, aircraft, etc.

(7) Targets vulnerable only to earth shock or penetration, such as underground installations, heavily protected tunnels, etc.

(8) Targets vulnerable only to penetration or shock in water, such as heavy shipping.

TYPES OF EXISTING WEAPONS

Types of existing weapons for aircraft consist primarily of projectiles, bombs, and rockets. Mines and torpedoes are relatively specialized weapons which are used to a lesser extent.

(1) Projectiles available are relatively small in size, going up to 105-mm shells, and are primarily impact and fragmentation weapons.

(2) Available rocket projectiles are relatively small in caliber, 4-1/2 and 5 in., but may become available in larger sizes. These are also primarily impact and fragmentation weapons.

(3) Available bombs may be divided into different categories:

(*a*) Primarily high-explosive bombs, ranging from 100-lb GP to 4000-lb LC bombs. Developments in progress include a 10,000-lb LC bomb. The British have gone to somewhat larger blast bombs.

(*b*) Primarily fragmentation weapons, ranging from 20-lb fragmentation bombs to 260-lb fragmentation bombs.

(*c*) Primarily penetration weapons, including semi-armor-piercing bombs, from 500 to 2000 lb, and armor-piercing bombs up to 1600 lb. The ratio of charge weight to total weight in these weapons runs from about 15% in the AP bombs to about 30% in the SAP bombs. The British have developed and the United States has now available 12,000- and 22,000-lb bombs with nearly 50% charge weight ratio for attack on highly resistant structures such as submarine pens, etc. There is in process of development by the AAF a 44,000-lb bomb of the same general type.

(*d*) Incendiary weapons, including the 4-lb magnesium bomb, the 6-lb gasoline gel bomb, and the 100- and 500-lb pyrotechnic gel bombs. Included in these should also be mentioned the use of droppable wing and belly tanks which contain up to 1000 lb of incendiary fuel and can be dropped by fighter bombers.

(*e*) Depth bombs, which are primarily light-cased high-explosive bombs for use in water.

FACTORS INFLUENCING SELECTION OF WEAPONS FOR ATTACK

GETTING WEAPONS TO THE TARGET

The consideration here in this report is not the problem of transporting weapons to the target area, but instead the problem of hitting on or near the target after the weapons have been carried to the region it is desired to attack. It is important in selecting a weapon to know not only what its capabilities are in causing damage but also what effort must be made in order to achieve the required number of hits that can produce damage. This is primarily a matter of accuracy with which projectiles, rockets, and bombs can be placed on a target. Under present conditions, the greatest accuracy is achieved by means of strafing with fighter planes; the next greatest accuracy by means of rocket attack with fighter planes or medium bombers. Considerably decreased accuracy can be achieved by dive- or glide-bombing attack by fighter bombers, and an even lower efficiency is obtained from medium altitude attack by medium bombers. The lowest accuracy is achieved by high-altitude attack. No method of guiding projectiles to a target so far developed to the point of general use has been more accurate than visual bombing or attack by other visual means. However, there is great promise in some of the methods that have been developed.

Merely as an indication of the difficulties involved, current bombing accuracy from medium-heavy planes at altitude of about 20,000 ft indicate that only about 20 to 40% of bombs dropped at a given aiming point will land within a circle of 1000-ft radius about the aiming point. For a particular target of relatively small size in the area, the chance of a hit is quite small. High-altitude attack on a target of a size of about 200 sq ft under present conditions will result in only about one-half of one percent hits. Consequently, the greatest increase that can be expected in improvement of efficiency with present methods of air attack lies in increasing the accuracy with which weapons reach the target. The increase from this source is potentially greater than that from any other factor within our control. With atomic bombs the amount of energy released is so large that a larger error in placing the bomb can be permitted than for ordinary high-explosive bombs.

COUNTERMEASURES

Consideration must also be given to enemy countermeasures in attack on a given target. Such countermeasures may involve camouflage by various means, smoke screens, decoy targets, as well as active resistance by means of air attack and anti-aircraft artillery. The effectiveness of countermeasures will determine to a great extent the weapons that should be used and the way that they can be used with the best chance for success. The choice of guided missiles may be dictated to save risk to presonnel even when the accuracy of such missiles is less than that of bombing from aircraft. With potential developments in the accuracy of guiding missiles, this means of attack may offer considerably greater advantages.

FUSING

The damage that a particular weapon can do is influenced materially by the time of initiation of the detonation. Control of the time of detonation is accomplished by means of fuses. Fuses usually have elements which prevent firing until certain conditions have been reached. For bombs a given amount of air travel is generally required to arm a fuse in order that it may fire upon later impact. Fuses presently available include the following:

(1) Proximity fuses or influence fuses which operate when they approach within a particular distance from a target.

(2) Impact fuses which are of three principal types.

(*a*) Instantaneous-action fuses.

(*b*) Relatively short-delay fuses, up to about 0.1 sec.

(*c*) Long-delay fuses, from several seconds to several days.

(3) Antidisturbance fuses.

(4) Hydrostatic fuses.

MAJOR UNCERTAINTIES

There are important questions concerning the proper choice of weapons for air attack that cannot be answered in the light of present knowledge or of experience to date. Such questions are the relative effect of extremely large blast bombs, the actual effectiveness of air burst compared with ground burst, the effectiveness of cratering bombs compared with air burst within buildings, the optimum size of large penetrating bombs, the effectiveness of cratering and violent earth shock, the possible advantages of fragmentation compared with blast, the most effective fusing of bombs, and the proper amount or proportion of incendiary bombs to achieve a desired degree of damage.

It is possible by means of proving-ground tests or similar laboratory experimentation to investigate the action of relatively simple structures subjected to damage from bomb bursts. But the vulnerability of a relatively complicated target such as a group of buildings cannot be studied adequately by theoretical means nor by proving ground experimentation. Increased knowledge of the proper choice of weapons with which to attack such targets can come only by observation of the effects of controlled bombing attacks in actual operations or by experiments in actual demolition of such targets.

PRESENT STATUS OF WEAPONS SELECTION

As a result of the work of various operations, analysis and research sections, by the Joint Target Group, and by NDRC and similar groups both American and British, certain trends have been established. The following conclusions appear to be accepted by all of the groups working on these problems:

(1) The most effective high-explosive bomb for attack of light industrial buildings is a GP bomb fused to burst between the roof and the floor. Greater damage was produced to the building and to its contents with this fusing then with intantaneous fusings, or with cratering bombs.

(2) Against heavy industrial buildings and heavy machinery, large cratering bombs or penetrating bombs are required to produce severe damage.

(3) Against relatively combustible construction, either residential or industrial, incendiary bombs were several times as effective, weight for weight, as any other type of bomb except possibly air burst of very large blast bombs.

(4) For domestic and industrial construction with relatively great resistance to penetration, the 4-lb magnesium bomb was more effective than larger incendiary bombs.

(5) Small bombs, blast bombs, and incendiary bombs had virtually no effect on submarine pens and heavy fortifications. Penetrating bombs or large general-purpose bombs are required.

(6) Against brick wall-bearing construction and against light wood-frame construction, blast bombs are most effective, and air burst at the proper height produces more damage than ground burst or cratering bombs.

FUTURE NEEDS

IMPROVEMENTS NEEDED IN PRESENT WEAPONS

Even with the availability of atomic bombs, it may be necessary, for isolated targets or other specialized targets, to use ordinary high-explosive weapons. Although the technique of using such weapons will probably be greatly different in the future than in the past, there are some developments that should be considered. These developments are appropriate even for attack by means of guided missiles or by homing missiles as well as for attack with present-day conventional bombing planes. A summary of required developments for the future, without reference to atomic weapons, guided missiles, homing missiles, and other related problems, is as follows:

1. *Bombs to Attack Underground Targets.*

Possibly these should be rocket assisted, for greater penetrating power.

2. *Shaped-Charge Bombs.*

The effectiveness of shaped charges for penetration should be examined. Possibly in connection with fragmentation weapons these have considerable utility, since the effectiveness of the fragmentation pattern is not seriously affected by the shaping of the charge to obtain penetration.

3. *Rocket-Assisted Bombs.*

These bombs are for greater penetrating capacity.

[redacted]

4. *Follow-Through Bombs.*

The British have in development a bomb consisting of a shaped-charge front to bore a hole, followed by a smaller bomb to penetrate and explode within the structure. Such developments should be fully investigated.

5. *Increased Case Strength For Bombs.*

In order to take advantage of the increased blast effects that come from higher quantities of explosives, means should be sought of strengthening the cases of bombs designed for penetration to permit them to carry greater quantities of charge. A more resistant case might have a fluted transition section between the nose and the main body to give greater resistance to crushing and rupture. Alternatively, developments in materials may be required to obtain the desired results.

6. *Development of Extremely Light Cases For Blast Bombs.*

Aluminum or magnesium alloy cases that permit a charge-weight ratio of almost 95% have already been considered by the British. Bombs with such light cases are entirely blast weapons and should preferably be fitted with proximity fuses.

7. *Controlled Fragmentation.*

Means of getting more uniform distribution of effective fragments are needed. The possibilities of using shrapnel should be considered. The development of fuses for permitting fragmentation bombs to enter a structure and burst within to destroy the contents should be investigated.

8. *Bombs For Low-Level Attack.*

Devices should be developed to make low-level attack more effective by preventing ricochet and bouncing of bombs from the targets. Possibly a plastic case with plastic explosive may be the answer.

9. *Nose and Tail Fuses With Variable Short Delay Time Settings.*

These would permit better selection of delay time, and also permit last minute changes of fusing when conditions make it desirable.

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ABSTRACT

A comparative analysis of new explosives. Desensitized Torpex is the most universal filler for bombs. It destroys 45% greater area than an equal volume of TNT and is sufficiently stable and insensitive so that it can be used in GP bombs. While a stoichiometric mixture of liquid hydrogen and liquid oxygen is more powerful, its sensitivity renders it impractical. Basic physical principles governing target vulnerability are described, and their application to problems of weapon selection is considered. Improvements needed in present weapons are also covered.

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A brief summary of the present status of knowledge concerning the properties and utilization of military high-explosives is presented. Particular attention is paid to the performance of high-explosives in blast bombs. Of the explosives in military use today HPX or desensitized Torpex appears to be the best all round filler for bombs. The means of damaging or destroying given targets with airborne weapons of the high-explosive or incendiary type are also investigated. Basic physical principles governing target vulnerability are described and their application to the problem of weapons selection is considered. Means of improving the effectiveness of ordinary high-explosive weapons are discussed and recommendations are made for specific improvements and developments in these weapons.

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