UNITED STATES STRATEGIC BOMBING SURVEY

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REPORT
OF
PHYSICAL DAMAGE
DIVISION

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CHAPTER I

FOREWORD

1. The Physical Damage Division of the U.S.S.B.S. was organized and given the primary task of determining the effects on various types of structures and equipment of HE (i.e. high explosive) bombs and IB's (i.e. incendiary bombs) as used in the Allied air offensive against strategic targets. To report on the effects of this bombing on production, transportation, etc., was the work of other divisions of the Survey.

2. Definition of Physical Damage. By common agreement when related to the results of bombings, physical damage is understood to mean that which requires the use of man-power or material for repair or replacement. Except when dealing with residences, in which case special terms are used (PDD 20)[I], damage to buildings is classified as:

a. Structural Damage, that which necessitates the repair or replacement of a main supporting member such as a floor slab, wall, beam, girder, truss, or column.

b. Superficial damage, that which is less serious than structural damage. However, when computing areas of superficial damage, destruction of panel (i.e., non-load-bearing) walls, glass, outside steps, cornices, etc., are disregarded and only that is considered which renders floor area unusable by the removal of its overhead cover.

c. Fire Damage

d. Mixed Damage, due partly to HE bombs, partly to fire.

3. Machine damage classifications are subject to less agreement. However, these, or similar, terms are commonly used:

a. Destruction, (or Totally Destroyed), the machine has value only as scrap.

[I] Physical Damage Division Report 20. Throughout this paper and without further explanation, references to division reports are made as above.

b. Heavy damage, a major part has been destroyed. Usually the machine would be returned to its manufacturer for repairs.

c. Moderate damage, a minor part has been destroyed which can be secured from the manufacturer or can be made and installed in the plant.

d. Light damage, destruction of electrical leads, or that which can be repaired by welding, etc.

Occasionally the last two of these classes are grouped together under either of the terms.

4. Sources of Information. In compiling this report slight use was made of reports by other organizations and of interrogations of German military and industrial personnel. Some facts were secured from the physical damage sections of plant reports written by other divisions of the Survey. The chief source of data, however, was the incident reports written by the division. These later record the findings of division personnel who accompanied industry teams on plant visits or, in many cases, the findings of teams which were organized and sent out by the division itself. A list of Physical Damage Division reports is attached hereto as Appendix A. For the convenience of those who may be interested, the reports are classified by industries in Appendix B.

5. Limitations of This Report. This report is an attempt to strike an average and draw some conclusions from the available data. Its weakness follows from the facts that: in many cases the source material is quite meagre; much of the material does not readily lend itself to summarization or averaging; and, of necessity, the work has been hurried. Concerning the first of the above facts, it is freely admitted that the material gathered, in spite of its seeming bulk, is but a small sample of what might have been secured with additional time and personnel. However, the group which has compiled the report sees no reason to suspect that consideration of a larger sample would have appreciably changed its conclusions. Concerning the second, even a slight acquaintance in the field with bomb damage, forces on the observer the conviction that there is enormous variation in results under essentially similar circumstances. Hence, two incidents at a single plant will defy a simple concise statement, and on occasions, observers at different plants will reach opposite conclusions. For this reason the serious student is advised to examine the individual incident reports of the division, which are believed, in general, to be of greater value than this present report.

CHAPTER II

HOW BOMBS PRODUCE DAMAGE

HE BOMBS

1. An HE bomb consists of a case, usually of steel, an explosive filling, and a fuze or fuzes. The function of the fuze is to detonate the filling at the proper time or place. The case serves one or more of several useful purposes. It protects the filling during storage and handling. It provides the confinement generally needed for high-order detonation of explosive. It permits the bomb to perforate or penetrate intact more or less resistant targets. Upon detonation it breaks up into fragments capable of doing damage.

2. An HE weapon causes damage in a number of different ways, namely, through contact explosion (combined damage effects); fragment; debris; air shock (blast), earth or water shock; and earth cratering due to destroying support or undermining. HE bombs also cause fires under certain conditions. As a secondary effect the deterioration of equipment from exposure to the elements is significant.

3. Different targets differ greatly in their vulnerability to each kind of action. For example, personnel, airplanes, light transport, lightly protected guns, and many types of machinery are vulnerable to fragmentation attack. Most buildings, except those of very heavy construction are vulnerable to air shock (blast), either interior or exterior. Very resistant structures above ground are most vulnerable to one of the following: contact explosion outside involving multiple causes of damage, interior air shock or blast, ground shock or cratering. Buried structures are vulnerable to contact or internal explosion or to earth shock.

4. Similarly, different weapons differ greatly in their ability to create each type of damage. A light cased bomb creates more blast, but generally produces fewer and lighter fragments than does a heavy cased bomb of the same weight. An AP (i.e. armor piercing) or SAP (i.e. semi-armor piercing) bomb has a comparatively small blast effect, due to the relatively small amount of explosive carried and to the confining action of its heavy case.

5. In selecting a weapon for a particular target it is desirable to match the maximum effectiveness of the former to the maximum vulnerability of the latter, subject to the requirement that perforation or penetration may have to be achieved without case failure, and to operational factors such as stowage and availability. In other words, targets that are vulnerable to blast are best attacked with bombs that create maximum blast.

6. <u>American HE Bombs.</u>

a. <u>AP</u> (Armor Piercing) bombs are used in the following sizes: 1000 lb. and 1600 lb. weight; the ratio of charge weight to total weight is about 15%. AP bombs are of small diameter and of stream lined shape, giving very high terminal velocity and also very high case strength. The filling is TNT or explosive D; fillings sensitive to shock are not suitable. This weapon is only used when perforation or penetration of extremely resistant targets (up to 5 ft. or 6 ft. of concrete

or 6-in. to 8-in. armor) is required. No nose fuze is used. Tail fuze is normally 0.08 sec. delay.

b. SAP (Semi-Armor piercing) bombs are used in the following sizes: 500 lb. and 1000 lb.; the charge weight ratio is about 30%. The slightly stream lined shape gives a high terminal velocity and the extra nose and case thickness insures high case strength. The filling was formerly Amatol, but later bombs are filled with TNT. These are normally used when considerable resistance to perforation has to be overcome (i.e. 3 ft. to 4 ft. of concrete or up to 3-in. armor). This bomb is normally fuzed only at the tail with the nose fuze hole closed by a steel plug.

c. Frag Bombs are used in the following sizes: 4 lb., 20 lb., 23 lb., 90 lb., and 260 lb. The charge weight ratio is from 10% to 15%. Except for the 4-lb. (Butterfly bomb) all of these have cylindrical cases of uniform thickness. The 90-lb. and 260-lb. bombs are wrapped with longitudinally notched heavy coil steel springs to give improved fragmentation. Fragmentation bombs are normally used with the instantaneous nose fuzes, however the proximity fuze can be used with these bombs (except the 4-lb. bomb which also can be fuzed for long delay or anti-disturbance). The 260-lb. bomb takes a non-delay tail fuze in addition to the nose fuze. Fragmentation bombs are used against personnel, planes, motor transport, light open field placements, etc., when in the open. Due to their instantaneous fuzing fragmentation bombs are not suitable for use against targets under roofs.

d. GP (General Purpose) bombs are used in the following sizes: 100 lb., 250 lb., 500 lb., 1000 lb., and 2000 lb., (larger sizes have been introduced recently). The charge weight ratio is approximately 50%. All these bombs may be fuzed both nose and tail with the usual delays, namely, instantaneous nose, non-delay tail, 0.01, 0.025, 0.1 sec. nose and tail, short and long delay. These bombs are the most used of all types. The case is heavy enough to allow perforation of fairly resistant targets (from 1 ft. to 3 ft. of concrete, depending on the bomb size). The fragmentation and blast are effective against normally constructed targets.

e. LC (Light Case) bombs are used in the following size: 4000 lb., with a charge weight ratio of 80%. It is fuzed either instantaneous or with proximity fuze since the case will not stand impact. The fragmentation is relatively ineffective. It is used only when extensive blast is desired.

7. The British series of bombs is generally similar to the American except for different designations, and some difference in sizes and construction. Normally only tail fuzes are used, however some bombs use as many as three tail fuzes.

a. The AP bomb is 2000 lb. with a charge weight ratio of 10%.

b. The SAP bombs are 250 lb. and 500 lb. with a charge weight ratio of 18%, which is materially less than the 31% of American SAP bombs.

c. The Frag. bomb is 20 lb. with a charge weight ratio of 15%.

d. The GP bombs are 40 lb., 250 lb., 500 lb., 1000 lb., 1900 lb., and 4000 lb. The charge weight ratio is 30% (Corresponds to American SAP).

e. The MC (Medium Capacity) bombs are 500 lb., 1000 lb., 4000 lb. 12000 lb., and 22000 lb. The charge weight ratio is 40% to 50% (Corresponds to American GP)

f. The HC (High Capacity) bombs are 2000 lb., 4000 lb., 8000 lb. and 12000 lb. The charge weight ratio is 66% to 75% (Corresponds to American LC).

8. Types of Damage.

a. Contact explosion. When a bomb explodes in contact, or nearly in contact, with a target several actions combine to produce the final result. Fragments from the bomb case cut up the adjacent elements of the target. Very high compressive stresses produced in the material by the blast wave cause complete disintegration near the point of detonation, and partial disintegration at greater distances. At the same time, large stresses are produced in the comparatively undamaged regions. These are propagated as stress waves to distant parts of the target and give rise to various localized damage zones at boundaries, connections, and other points of discontinuity. The effect of detonation in contact with a concrete slab illustrates this behavior. Immediately beneath the point of detonation a hole or crater is formed. Surrounding this crater is a zone of concrete that is cracked and weakened. If the slab is of the proper thickness there will be a second crater formed on the far surface of the slab due to scabbing of concrete at the surface. The concrete between these craters may or may not be unharmed, depending on the thickness of slab. For thin slabs the craters will meet, resulting in complete perforation, while a very thick slab will normally show no effect on the far side.

b. Fragmentation. This is damage produced by missiles consisting of bomb component fragments. Only GP and Fragmentation Bombs are effective producers of fragments. The light case bombs have too few and too light fragments while the AP, and to a less extent, the SAP bombs give fragments relatively large and of low velocity making the bomb generally ineffective as a fragmentation weapon. When a bomb explodes, the case breaks up into fragments varying in size from very small to several times the case thickness The fragments are not distributed uniformly about the bomb, but tend to be concentrated in one or two zones. The most important spray (the equatorial spray) coincides approximately with the equatorial plane of the bomb. More exactly, the equatorial spray is directed about 10 degrees either ahead of, or behind the equatorial plane of the bomb, depending on whether tail or nose initiation is used. Under certain conditions this difference between nose and tail initiation becomes important, as in attacking machinery housed in one-story structures. In high order detonations fragment velocities range from about 2,000 to as much as 8,000 or more ft. per second, depending on charge weight ratio and type of explosive. Tables are available for /fragmentation and GP bombs, showing fragment patterns and velocities as well as densities of perforation achieved against various thicknesses of armor plate at different distances. (See Terminal Ballastic Data, Vol. I-Bombing, Office of Chief of Ordnance, August 1944).

Fragmentation is most effective against compact targets containing a large proportion of vital elements, for example, personnel, all types of

machinery, transportation equipment, airplanes, electrical devices, weapons. Such targets are usually fairly immune to any kind of shock, while the high proportion of vital elements makes most fragment hits effective.

The proper fragmentation weapon to use depends mostly on the vulnerability of the target, that is, on the amount of protection that must be perforated to produce an effective hit. The larger bombs have heavier fragments, consequently an increase in target resistance normally requires an increase in bomb size. For very "soft" targets, such as personnel or light, delicate mechanisms, the smallest fragmentation bombs, i.e. the 4 lb., and 20 lb., or 23 lb., are most efficient, weight for weight. For devices protected by a $\frac{1}{2}$ in. or more of steel plate such as armored guns, large transformers, armored cars, etc., 260-lb. Frag or 500-lb., and 1000-lb. GP bombs are most effective. The use of Frag bombs is limited to targets not under cover, since instantaneous or proximity fuzing is always used with them.

Fragmentation is not an effective means of damaging structures. For light single members (say roof purlins) fragmentation will sometimes cause enough damage to require replacement. Heavy beams or columns, wall panels, floors etc., may be scarred or perforated by fragments, but can be repaired quite easily unless they are so close to the point of detonation as to make it uncertain whether blast or fragmentation played the major role.

c. Debris. Structural members, floor and roof slabs, and rock particles may be effective damaging agents against fairly vulnerable targets such as personnel and delicate mechanisms. Such missiles are larger and slower than bomb fragments. Light machine tools in very long-span concrete roofed buildings have been found to suffer very considerably from debris.

d. Air, earth and water shock. Fundamentally, these are alike inasmuch as the effect is due to pressure transmitted to the target through the medium between it and the bomb. Air shock, or blast, is the most important, since most targets are above ground. A blast wave is characterized by a very steep front, corresponding to an instantaneous pressure rise, followed by a decrease to sub-atmospheric pressures, then a gradual return to normal. The peak pressure and the positive impulse (the impulse is the product of the time during which the pressure exceeds atmospheric multiplied by the average pressure during that interval) are the most important characteristics of the wave. For normal structures and the sizes of the bombs hitherto used, damage is generally considered to depend mainly on impulse. This conclusion, which is supported by experience, has permitted the extension of the very limited conclusions first drawn as to the damage areas of different weapons against different targets to various other combinations of targets and weapons. It is one purpose of this Survey to add to present knowledge and to correct the extrapolations that have been made.

For structures whose periods of vibration are short compared to the duration of the positive pressure phase it is probable that damage from external blast will depend mostly on the peak pressure of the wave. Due to the short durations of pressure pulses from the bombs used hitherto this situation has not yet been important; it may become important with extremely powerful bombs.

It has been shown that if damage depends only on impulses, then for external blast the efficiency of bombs increases with the bomb size of a

given type. On the other hand, if damage depends only on peak pressure it can be shown that the efficiency of bombs decrease with an increase in bomb size. Consequently for external blast, the situation appears to be the following:

(1) For small bombs an increase of size increases the area of destruction per unit weight of bombs;

(2) For large bombs an increase of size decreases the area of destruction per unit weight of bombs.

Therefore, if efficiency is measured in terms of damage per weight and if all bombs are used in the same way and employ the same explosive, there will be an optimum bomb size for each type of target. The above considerations apply only to the case of external or unconfined blast. In comparing the effects of explosion within the outside of a structure several additional factors become important. Confined explosions exert greater impulses than unconfined. Furthermore, structures are generally less resistant to internal than to external forces, being designed for the latter. On the other hand, an explosion inside a structure is less effective against neighboring structures than is an unconfined explosion at the same distance. So far as confined or internal explosions are concerned the optimum size of charge is one just big enough to create the required damage to the structure in which it detonates.

External blast is comparatively ineffective in small bombs; however, the efficiency increases with size. For external blast, case weight can be kept to a minimum, allowing most of the munition weight to be explosive, while cases of at least GP bomb thicknesses are needed for internal blast to insure penetration without case failure.

External blast is effective only against buildings of normal or less strength. External blast is not an efficient use of HE bombs against very resistant buildings or against gun emplacements, air raid shelters and the like. For these, internal blast is more effective, the effectiveness depending on the degree of confinement.

e. Earth Shock. Buried, or partly buried targets are frequently best attacked through ground shock. This is also true of those surface structures whose foundations are vulnerable.

An underground explosion causes ground movements and high pressures in the surrounding earth. Any structure in or on the ground in this vicinity must resist both effects. Very small structures move easily, consequently are less likely to be damaged, than are large structures. The distance at which damage can be expected is generally small, of the order of two or three crater radii from the explosion. Tests in the USA and Britain have shown the nature of the relation between damage, distance, and mount of explosive (See eg. NDRC Div 2, Weapon Data Sheet 6A5, Underground R/C Walls - Damage by Earth Shock).

f. Underwater Shock. This is generally similar to air blast and earth shock, For this reason, and because no examples of underwater shock have been examined by the Physical Damage Division, no further discussion is given here.

g. Cratering. A bomb exploding underground at not too great a depth will produce a crater. Any structure or other object extending over or into the crater may be caused to settle through removal of support. Cratering is especially effective against strongly framed buildings having shallow footings. It is also an important cause of damage to machines or equipment of considerable length or where alignment is important, as in shafting or in coupled machinery.

h. Fire from HE. In an appreciable number of cases HE bombs start fires. This occurs mainly where highly combustible materials, oils, gases, combustible dusts, etc. are present and are released by the bomb. Ignition may be caused by the hot gases of the explosion when detonation occurs very close to the ignitible material, as when a bomb explodes in an oil or gas container. Another cause of ignition is the overturning of stoves and heaters, shorting of electrical equipment and the like. In certain high temperature-high pressure processes (as in refineries, and synthetic oil and rubber plants) the hot liquids and gases are able to ignite spontaneously when released.

INCENDIARY BOMBS

9. Ways of Firing a Target. There are two ways in which incendiaries may fire a target. One is to ignite combustible material in the target. The second is to carry combustible material to the target in the bomb. As a practical matter, the second of these two methods is not very important. The size of incendiaries is necessarily limited. Even the largest ones now in use, or projected, do not produce a very big fire, that is, do not in themselves provide enough combustible material to cause a big fire.

In setting out, therefore, to damage a target, things in the target must be looked for to cause fire damage. Failure to understand this has sometimes led to erroneous conclusions as to the steps involved in bringing about destruction or damage.

10. Flight and Penetration. The steps in setting fire to a target with an incendiary begin with the dropping of the incendiary. It must have sufficient stability in flight to come down in such a manner that it will most effectively get into the target. This usually means going through the roof. The velocity must be sufficient to carry the bomb through the type of roofs and floors known to be in the target without deformation to prevent normal operation.

11. Finding Combustible Centers. Once having penetrated into the target building so as to operate as designed, the bomb must fall into or near some material to which it can set fire. Therefore, the way in which combustible material is distributed throughout a target is important. It determines the probability of the bomb striking sufficiently near to combustible material suitable to respond to its fire starting abilities. In dwelling houses and other buildings with wooden floors and roofs, there are a good many places where a bomb can come to rest on combustible material. In industrial plants, the floors and building structure may be fire-resistive or non-combustible. Hence, the bomb must find wooden partitions, piles of wooden boxes, such as "tote" boxes, wood finish or furniture. In some industries it may have to be initiated near or on piles of combustible stocks, such as rubber for example, or spilled flammable liquids.

Usually the kind of combustible material which would be ignited by an incendiary bomb is that which is of the order of kindling: paper, excelsior, thin pieces of wood, cardboard cartons, light furniture, draperies and the like. Heavy furniture, heavy woodwork and flooring are relatively more difficult to ignite. Many of the incendiaries so far developed cannot be counted upon to always ignite combustible material unless it is in the form of highly combustibles.

12. Chance of Igniting Combustibles. The next consideration is the chance that an incendiary bomb will ignite combustible material into which it falls. Of the various types of incendiary bombs some are necessarily more efficient in igniting a specific type target, than are others. It is not practicable to generalize about their relative fire-starting abilities, because it is necessary to consider how they will perform against a variety of wooden or other combustible surfaces. Because the combinations in which these surfaces may be arranged is infinite a very large number of variables is involved.

A small magnesium bomb (2-lb. or 4-lb.) will spurt light sparks of magnesium and thermite in its first minute of operation. Thereafter it settles down to steady burning for a period of about 3 minutes, during this period a person can approach within a few feet of the burning bomb. Obviously, only paper, thin wood and other readily combustible material can be ignited from such a fire.

The small oil bomb (6-lbs.) throws out a small mass of burning gel. In hitting a surface this breaks up into smaller masses, no one of which makes a big fire. It, too, can be closely approached and therefore is most likely to touch off only light combustibles.

The larger oil bombs (30-lbs., 100-lbs., 250 lb., and 500-lbs.) are more effective. They will affect a larger area because of the greater total amount of fuel in the bomb. As a rule they break up into small masses so that the fires they start must be in materials that take fire relatively easily.

The 30-lb. and larger bombs can be expected to ignite fairly heavy combustible material in some proportion of cases. But, even the largest of these bombs produces a relatively small fire at the beginning. If they are promptly attacked with even a 1/8 in. diameter hose stream discharging as little as 2 or 3 gallons of water a minute, there is a very good chance of controlling the fire.

13. Preliminary Fire Spread. a. Next in the steps in setting fire to a building is the development of the fire from the point where the bomb initiates fire. This depends on a chain of combustible material in the immediate vicinity of the point of the bomb incident.

b. In dwelling houses there is fairly continuous chains of combustible material. The floors and furniture will usually burn and also in some cases the wall finish.

c. In industrial plants, a great variety of factors determine whether a fire once started will spread. A few of these factors can be mentioned to show how complicated this particular part of the process is to appraise.

(1) Occupancy Combustiblity Scale. Storage rooms in industrial plants may be a good place to start. These usually offer a large amount of material, most of it combustible, covering a large percentage of the floor area. Even when the goods stored are non-combustible, such as metal parts, they are often packed in cardboard containers or wooden boxes. Often they are stored on wooden shelving. A particularly good example of a highly combustible occupancy is the store room for wooden patterns in a general machine shop. As a measure of occupancy combustibility of this type the pounds of combustible material per square foot would be a relatively high figure. Also there would be a continuous chain of combustible material over the entire floor area. If this is taken as the upper end, we can visualize other occupancies on a rough scale compared to it. Lower ranges in the scale involve less and less in pounds of combustible material per square foot, wider and wider spaces between groups of material, and a poorer and poorer chain of combustibles. On such a scale the next range will include certain assembly operations where a lot of small items are put together. Small items are often handled in combustible "tote" boxes or on crowded combustible benches. Still lower on the scale would be the heavier assembly operations such as those involved in air frame assembly.

When the machine shop and metal working occupancies are reached, the occupancy combustibility is quite low. Lowest of all will be such occupancies as boiler houses and power houses or rooms where the principal machines would be compressors, pumps, generators and the like.

The foregoing is by no means a complete catalogue of combustibility ratings. It may be seen, however, that they affect the extent to which a fire once started will spread.

(2) Spread Due to the Structure. In addition to occupancy causes, there are factors in the structure of the building affecting the likelihood that a fire once started will spread. In many industrial buildings, the only major combustible material may be a wooden roof which is often some height above the floor. An incendiary must come through the roof, land on the floor, and then ignite some combustible material on which to cause flames extensive enough to ignite the roof. Consequently the higher the roof the more difficult it is for it to be reached by a fire on the floor.

(3) Walls. Any wall tends to slow down a fire as the fire must find openings through which to spread. Another

type of wall is designed as a fire wall. This, by definition, is a wall which will stop the spread of fire. Usually it is construction of brick and is so thick and resistant to heat transfer that a complete burnout may occur on one side without sufficient heat being developed on the other to permit the ignition of combustible materials.

(4) Fire Divisions. A fire division, which is the area of a building within fire walls, limits the maximum size of an individual fire. Even though theoretically possible, complete burnout within a fire division does not always occur; first, because the arrangement of combustible material within the division may not be continuous; second, because there may be partitions, often of non-combustible material, which are not substantial enough to be considered as fire walls, but which will retard the spread of fire.

The foregoing discussion, for simplicity, has been principally in terms of single-story buildings. In multi-story buildings, the floors, if fire resistive, act as barriers to the spread of fire from floor to floor. Stairway openings and elevator shafts, however, are avenues for the spread of fire.

The spread of fire from building to building is principally a matter of space between the buildings, but much judgment is required to determine whether an air gap is sufficient to stop the spread of fire in a given case. Some of the factors to be taken into account are (1) combustibility of walls, (2) combustibility of occupancies, (3) size and intensity of the fire, (4) the area of exposed walls presented to one another, and (5) size of wall openings.

14. Types of Construction. The combustibility of the building structure is a factor which operates in conjunction with the occupancy and arrangement factors described. For convenience, the types of construction are grouped into four classes: combustible (C), non-combustible (N), fire resistive (R), and mixed construction.

a. Combustible construction includes those buildings which have a roof and sometimes walls of combustible material. The burning of the combustible portion can normally be expected to cause structural damage.

b. The non-combustible type has no significant amount of combustibile material, but the structure is damageable by fire in the contents. Examples of this are concrete, asbestos, corrugated iron, pre-cast or poured-in-place cement or gypsum supported by exposed (bare) steel. Reinforced concrete less than $2\frac{1}{2}$ in. thick is also classed in this category.

c. In fire-resistive construction, there is no significant amount of combustible material in the structure and the structure will withstand all except the most intense fire. Examples are reinforced concrete where the members are $2\frac{1}{2}$ in. or more thick and where there is no unprotected steel; buildings, usually multi-story, where the steel

supporting the concrete floor and roof slabs is protected by at least 2 in. of concrete covering; the Zeiss-Dywidag construction where an arch of reinforced concrete $2\frac{1}{2}$ in. to $3\frac{1}{2}$ in. thick is used.

d. Mixed construction includes combinations of the foregoing types. A common example is a multi-story building with reinforced concrete construction except for a combustible wood roof.

15. Engineering Appraisal of Fire Vulnerability. The appraisal of the very complicated series of steps which affect the operation of incendiaries on a target would appear at first glance a somewhat hopeless task. However, it is possible to find fire protection engineers who have had experience with exactly the factors enumerated. Many of these have inspected in excess of 1000 plants and have been trained to look for the factors mentioned above. Their advice might well be sought in selecting targets for attack by incendiaries.

HIGH EXPLOSIVE BOMB DAMAGE TO BUILDINGS AND INSTALLATIONS

1. General. This part of the report deals with HE weapons and their damaging effects upon structures and installations under the following headings:

a. Industrial type buildings.

b. Heavy structures (gun emplacements, submarine pens, fortifications, coking plants).

c. Bridges.

d. Chimneys (masonry type).

e. City areas.

2. HE bomb damage only, has been considered in the text and tabulations except in the section which covers City areas. In this part of the report, HE bomb damage includes any fire damage which was caused by the detonation of HE weapons but does not include any "Mixed" damage which could have been caused by the joint action of HE and IB weapons.

3. The material analyzed has been extracted from Physical Damage Division reports covering the results of field surveys of the various targets. Table 4 lists the Physical Damage Division reports by number and title from which the pertinent data for industrial type buildings has been taken. The report numbers and titles covering source data for other installations have been referred to in the text.

4. The attempt has been made in the report to associate the HE bomb damage effects upon buildings with the structural vulnerability classification of the structure and the weapon used. In certain of the vulnerability classifications sufficient data for an effective study are lacking and that limitation must be recognized. It will be noted that the foregoing applies only to U.S. and British bombs, principally of the 500-lb. and 1000-lb. sizes. A large bomb detonation (4000-lb. and above) invariably affects buildings of more than one structural type, due to its large near-miss radius, whereas the smaller bomb has a smaller near-miss range in causing structural damage. The smaller size bomb effects are therefore more likely to be confined to the structure directly adjacent to their points of impact. This is not true of the larger sizes of bombs and the measure of their effectiveness should be obtained from the section of the report dealing with mean areas of effectiveness of HE weapons.

HE Weapons Used.

5. The following HE weapons were used to inflict damage on industrial targets which are listed in Table 4:

	Size (lbs)	Type	Fuzings (Sec.)	
			Nose	Tail
U.S.	100	GP	0.1	0.01
	250	GP	Inst	-
			0.1	0.025
	500	GP	0.1	0.01
			0.1	0.025
	1000	GP	0.1	0.01
			0.1	0.025
British	500	MC	0.025	
	1000	MC	Inst 0.01 0.025	
	2000	HC	Inst	
	4000	HC	Inst	
	8000	HC	Inst	
	12000	HC	Inst	

GP = General purpose

MC = Medium capacity

HC = High capacity

6. HE weapons used against other installations are listed below:

Target	Size	Type	Fuzing	
Submarine Pens	Br.12000 lb.	Tallboy	0.5 Sec. delay 11.0 Sec. delay 25 to 30 Sec. delay	
			Nose	Tail
Coking Plant	U.S. 500 lb.	GP	0.1 sec.	.01 sec.
			0.1 "	.025 "
Gun Emplacement	U.S.1000 lb.	GP	0.1 "	.01 "
Bridges	U.S.1000 lb.	GP	0.1 "	.01 "
			0.1 "	Non-delay
City Area	U.S. 100 lb. U.S. 250 lb. U.S. 500 lb. U.S.1000 lb.	GP GP GP GP	0.1 Nose	.01 Tail .025 "

7. HE Bomb Damage to Industrial Buildings. Table 4 contains a compilation of data for all damaged buildings included in the targets as listed in the Table. The buildings damaged were principally of the factory type and the various appurtenant buildings usually found in industrial plants; the structures were predominantly single-story but a number of multi-story buildings were also damaged.

Table 4 lists twenty-two (22) different targets and a summary of the HE bomb damage suffered by these objectives is given below:

No. of Targets.	Plan Area of the Damaged Bldgs. Acres.	Total Floor Area of Damaged Bldgs. Acres.	Total Area of Struct'l Roof Damage Acres	Total Area of Struct'l Floor Damage Acres.
22	217	253	83	15

Total Area of Supf'l Damage Acres	Fraction of Struct'l Roof Damage	Damaging HE Bombs Tons	Struct'l Damage (Roof plus Floor) in Acres/Ton
47.5	.38	420.3	0.23

One Ton = 2000 lbs.

Fire damage to roof structures, caused by HE bombs, was insignificant in amount but this category of damage accounted for 20.4% of the total area of floor damage listed. The difference in the amount of HE-fire damage suffered by roofs and floors was probably due to the ignition and burning of contents on the floors caused by detonation of the bombs.

8. Damage to Structural Types of Buildings caused by U.S. and British 500-lb. and 1000-lb. HE Bombs. Damage and bomb data has been lifted from the reports, listed in Table 4, referring to U.S. and British 500-lb. and 1000-lb. HE bombs, but only those items of damage which were definitely tied back to a specific weapon and to a specific structural type were extracted to avoid confusion with the effects of other weapons. Buildings of different construction have different vulnerabilities to HE bombing, in general, and a division of buildings into structural types has been made in order to compare the damage to the respective types caused by a given weapon. The structural types are indicated below:

Symbol	Description
	Single-Story Buildings
1/a	Masonry load bearing wall types
1/b	Light factory types; steel or wood framed
1/c	Heavy steel framed or those containing runways that support heavy cranes.

Symbol	Description
1/d	Hangar and Aircraft assembly types; steel, timber or reinforced concrete framed roofs
1/c	Factory reinforced concrete framed or shell types
1/f	Miscellaneous buildings of light construction.
	Multi-Story Buildings
M/a	Masonry load bearing wall types or those of composite construction
M/b	Steel framed
M/c	Reinforced concrete framed or flat slab construction.

The above structural types have been used in Table 1-3, which compare the damage effects of U.S. and British, 500-lb. and 1000-lb. bombs.

9. Table 1 separates U.S. and British bombs of the 500-lb. and 1000-lb. sizes by the fuzings used; structural roof damage, the number of bombs inflicting the damage and the structural roof damage in acres/ton is indicated for the purposes of comparison. Due attention must be given to the number of cases involved; the reliability of the values in column 10 is contingent upon the number of buildings attacked with the weapon.

a. Few cases were available for the British bombs of the 500-lb. and 1000-lb. sizes and the data for the 1/c, 1/c and 1/f structural types for the 1000-lb. MC appears to be the best.

b. U.S. 500-lb. GP - The most reliable data is shown for the 1/a, 1/b and the 1/f structural types. The 0.01 sec. tail delay fuze produced more damage per ton of HE than the 0.025 sec. tail delay fuze, except for type 1/f where the result was nearly equal. Data for the multi-story type in Table 3, are inadequate in amount for conclusions.

c. U.S. 1000-lb. GP - This weapon does not appear to be as efficient for causing damage as the 500-lb. GP, but additional incidents are required for a true evaluation. The 0.025 sec. tail fuze fitted to this weapon appears to produce more damage than the 0.01 sec. tail fuze.

d. British 500-lb. MC - Insufficient data does not permit any appraisal of this weapon to cause damage.

e. British 1000-lb. MC - the best data for this weapon is shown against the 1/c structural type where the 0.01 sec. delay fuze

seems more efficient in producing damage. Against the 1/f structural type the 0.025 delay fuze was better than non-delay but an insufficient number of cases will not support a conclusion. The 1000-lb. MC fuzed 0.025 sec. delay shows better results against the 1/c structural type than the U.S. 1000-lb. GP. fuzed 0.025 sec. tail delay.

10. Table 2 has been prepared to indicate the effect of U.S. 500-lb. and 1000-lb. GP bombs against the structural types, regardless of fuzings. Incidents have been added to those shown in Table 1 to include those buildings which were attacked with bombs fitted with mixed fuzings. Sufficient data for accurate study are not available for the following items:

HE Weapon	Structural Type
U.S. 500-lb. GP	1/c
Br. 1000-lb. MC	1/a, 1/f.

Table 2 suggests that the U.S. 500-lb. GP is a more efficient weapon against the various structural types than the U.S. 1000-lb. GP. The British 1000-lb. MC type shows superiority over the U.S. 1000-lb. GP in attacking structures of type 1/c, but is inferior against type 1/c structures, on the basis of the data listed.

Sheet 1 of 2

TABLE ~~2~~ 3

EFFECTS OF HE BOMBS AGAINST SINGLE STORY STRUCTURAL TYPES OF BUILDINGS ALL FUZINGS

BOMB DATA		Areas of Struct. Roof Damage	NUMBER OF BOMBS			Total Tons of HE	Struct. Roof Damage A/Ton
Size	Type		Direct Hits	Near Misses	Total		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
STRUCTURAL TYPE 1/a							
U.S. BOMBS							
500	GP	156.8	24	25	49	12.25	0.29
1000	GP	60.8	13	11	24	12.00	0.12
BRITISH BOMBS							
1000	MC	22.7	1	1	2	1.0	0.52
STRUCTURAL TYPE 1/b							
U.S.BOMBS							
500	GP	158.5	38	19	57	14.25	0.26
1000	GP	221.8	33	20	53	26.5	0.19
STRUCTURAL TYPE 1/c							
U.S.BOMBS							
1000	GP	102.7	31	5	36	18.0	0.13
BRITISH BOMBS							
1000	MC	90.0	16	5	21	10.5	0.20
STRUCTURAL TYPE 1/d							
U.S.BOMBS							
500	GP	149.5	38	3	41	10.25	0.34
STRUCTURAL TYPE 1/e							
U.S. BOMBS							
500	GP	15.0	4	3	7	1.75	0.20
1000	GP	145.4	8	4	12	6.0	0.56

Revise

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Sheet 2 of 2

TABLE ~~2~~ 3
EFFECTS OF HE BOMBS AGAINST SINGLE STORY STRUCTURAL TYPES OF BUILDINGS
ALL FUZINGS

Revise

BOMB DATA		Areas of Struct. Roof Damage	NUMBER OF BOMBS			Total Tons of HE	Struct. Roof Damage A/Ton
Size	Type		Direct Hits	Near Misses	Total		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
BRITISH BOMBS							
1000	MC	35.6	8	2	10	5.0	0.16
STRUCTURAL TYPE 1/f							
U. S. BOMBS							
500	GP	72.2	26	12	38	9.5	0.17
BRITISH BOMBS							
1000	MC	40.7	5	2	7	3.5	0.27

Areas given in 1000's of square feet.
One ton = 2000 lbs.

~~Primary~~
~~Secondary~~
~~T of O~~
~~[illegible] tonnages which must be used to effectively deliver a given tonnage.~~

~~Weather~~
~~Flak~~
~~Fighter opposition~~
~~Air Base area~~
~~Height of attack~~
~~[illegible]~~
~~All [illegible] cases not [illegible]~~
~~Japanese incidents [illegible] visited~~

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Revise

TABLE ~~6~~ 4

EFFECTS OF HE BOMBS AGAINST MULTI-STORY TYPES OF BUILDINGS

BOMB DATA		FUZING		AREAS OF DAMAGE		NUMBER OF BOMBS			TOTAL TONS OF BOMBS	TOTAL STRUCT. DAMAGE A/TON	NO. OF CASES++
SIZE	TYPE	NOSE SEC.	TAIL SEC.	STRUCT. ROOF	STRUCT. FLOOR	DIRECT HITS	NEAR MISS	TOTAL			
Structural Type M/a (Specific Fuzings)											
U.S. Bombs											
500	GP	0.1	0.025	-	6.0	-	2	2	0.5	0.27	3
British Bombs											
1000	MC	-	0.025	7.0	17.0	2	-	2	1.0	0.78	2
Structural Type M/a (All Fuzings)											
U. S. Bombs											
500	GP	All		51.1	6.0	10	6	16	4.0	0.33	-
Structural Type M/b (Specific Fuzings)											
U. S. Bombs											
500	GP	0.1	0.025	8.1	-	5	3	8	2.0	0.09	3
1000	GP	0.1	0.01	8.2	8.2	5	-	5	2.5	0.15	1

++ A case is a single building or a single unit of a building complex consisting of more than one structural type.

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HEAVY STRUCTURES.

11. Submarine Pens. Reports 10 and 39 cover the results of bombing attacks on the submarine pens located at Brest, France, and Hamburg, Germany respectively. In both instances 12000-lb. (Tallboy) bombs, employing various fuze settings, were the weapons used in the attacks. Results of the surveys show that little effective damage was accomplished and in neither case were the pens rendered unserviceable. A description of each target and summary of damage inflicted follows:

12. Submarine Pens at Brest, France (PDD 10). This structure was constructed of reinforced concrete of excellent design and strength. It was 1200 feet long by 600 feet wide and contained 15 submarine pens. Original construction had a flat reinforced concrete roof varying in thickness from 12 ft. 8 in. to 14 ft. However the protective quality of the roof was supplemented by several methods on different roof areas. In some areas an additional 5 ft. of reinforced concrete was poured directly on the original roof without bonding by reinforcement steel. On other areas precast concrete blocks were laid, and on others a slightly pitched roof of reinforced concrete was erected. In the latter areas an air space existed between the original roof and supplementary protection. This pen received nine direct hits by 12000-lb. (Tallboy) British bombs. Five were fuzed for 11 sec. delay action and four were fuzed 0.5 sec. delay. In addition two of the same type bombs fuzed 0.5 sec. detonated near the rear side of the pen. In all direct hits the bombs failed to penetrate the roof prior to detonation. Strikes on roof spans either resulted in craters with accompanying under-roof spalling or hour-glass shaped openings. Strikes on areas directly over heavy partition walls resulted in roof craters and spalling on the underside of the roof and partition wall. In no case did serious structural damage occur such as roof collapse or wall cracking. Minor damage occurred to interior facilities such as crane rails, air and electric lines, walkways and hand rails by falling debris from the roof spalls. The two strikes at the rear of the structure caused no damage to the main building but demolished a few nearby buildings of light construction.

13. Submarine Pens at Hamburg, Germany (PDD 39) This structure was constructed of reinforced concrete of excellent design and strength. It was 518 ft. long by 442 ft. wide and had a flat reinforced concrete roof varying in thickness from 10 ft. to 11 ft. 6 in. This pen received six direct hits by 12000-lb. (Tallboy) British bombs all fuzed 25 to 30 sec. delay. In addition one near miss by the same type bomb and same fuzing occurred 100-ft. from the west sidewall of the structure. As in the cases of the strikes on the pens at Brest, France, none of the direct hits penetrated the roof prior to detonation. Crater data and interrogation of witnesses resulted in the conclusion that all bombs detonated non-delay after penetrating about 3 ft. into the roof concrete. Strikes on the roof resulted in each case, of hour-glass shaped openings ranging in lip diameter from 14 to 25 ft. and in throat diameter from 9 to 16 ft. with the minimum section occurring from 3 to 5 ft. below the roof surface. No major structural damage, such as roof collapse or fracturing, resulted from the hits. Minor damage to operating devices inside the pens resulted

14 ~~12~~. Submarine Pens at Brest, France (PDD 10). This structure was constructed of reinforced concrete of excellent design and strength. It was 1200 feet long by 600 feet wide and contained 15 submarine pens. Original construction had a flat reinforced concrete roof varying in thickness from 12 ft. 8 in. to 14 ft. However the protective quality of the roof was supplemented by several methods on different roof areas. In some areas an additional 5 ft. of reinforced concrete was poured directly on the original roof without bonding by reinforcement steel. On other areas precast concrete blocks were laid, and on others a slightly pitched roof of reinforced concrete was erected. In the latter areas an air space existed between the original roof and supplementary protection. This pen received nine direct hits by 12000-lb. (Tallboy) British bombs. Five were fuzed for 11 sec. delay action and four were fuzed 0.5 sec. delay. In addition two of the same type bombs fuzed 0.5 sec. detonated near the rear side of the pen. In all direct hits the bombs failed to penetrate the roof, prior to detonation. Strikes on roof spans either resulted in craters with accompanying under-roof spalling or in hour-glass shaped openings. Strikes on areas directly over heavy partition walls resulted in roof craters and spalling on the underside of the roof and partition wall. In no case did serious structural damage occur such as roof collapse or wall cracking. Minor damage occurred to interior facilities such as crane rails, air and electric lines, walkways, and hand rails by falling debris from the roof spalls. The two strikes at the rear of the structure caused no damage to the main building but demolished a few nearby buildings of light construction.

15 ~~13~~. Submarine Pens at Hamburg, Germany (PDD 39) This structure was constructed of reinforced concrete of excellent design and strength. It was 518 ft. long by 442 ft. wide and had a flat reinforced concrete roof varying in thickness from 10 ft. to 11 ft. 6 in. This pen received six direct hits by 12000-lb. (Tallboy) British bombs all fuzed 25 to 30 sec. delay. In addition one near miss by the same type bomb and same fuzing occurred 100-ft. from the west sidewall of the structure. As in the cases of the strikes on the pens at Brest, France, none of the direct hits penetrated the roof prior to detonation. Crater data and interrogation of witnesses resulted in the conclusion that all bombs detonated non-delay after penetrating about 3 ft. into the roof concrete. Strikes on the roof resulted in each case, in ~~of~~ hour-glass shaped openings ranging in lip diameter from 14 to 25 ft. and in throat diameter from 9 to 16 ft. with the minimum section occurring from 3 to 5 ft. below the roof surface. No major structural damage, such as roof collapse or fracturing, resulted from the hits. Minor damage to operating devices inside the pens resulted from falling debris. The near miss caused settlement and lateral displacement of the west wall but did not materially effect the stability of the structure nor prevent its continued use as a submarine pen.

from falling debris. The near miss caused settlement and lateral displacement of the west wall but did not materially effect the stability of the structure nor prevent its continued use as a submarine pen.

14. **Coking Plants**. Physical Damage Report 13 covered the survey of bomb damage to coking plants, located at Montigny and Liege, Belgium. In addition the Munitions Division of the Survey issued report "The Coking Industry in Germany". The interested reader will find details in these two reports.

15. **Gun Emplacements**. Physical Damage Division Report 1 covers the results of bombing attacks on four 15-cm gun emplacements located near Longues, France. The target consisted of an area which included not only the four separate gun emplacements but also communication tunnels and trenches, personnel shelters, ammunition storage shelters and observation posts. The area was well saturated with bomb hits which included two direct hits on structures and two near-miss hits to structures. Positive identification of the size and fuzing of the bombs was not possible but in the opinion of the survey party all strikes were made by 1,000-lb. GP bombs fuzed with 0.1 sec. nose and 0.01 sec. tail fuzes. Damage resulting from these four hits is described in the following:

a. One direct hit and two near misses occurred at Gun Emplacement 2. The direct hit struck on the roof of the left wing which, at the point of contact, was estimated to be four to five feet in thickness and was constructed of reinforced concrete. This bomb penetrated the roof and resulting blast destroyed the westwall and fractured the east interior wing wall from the ceiling to the floor. One near miss, striking three feet from the front corner of Emplacement 2, badly cracked the concrete gun base probably putting the gun out of action. Another near miss two feet from the right wing of the emplacement apparently caused no material structural damage.

b. One direct hit occurred on the roof of an ammunition storage shelter. This building was constructed of reinforced concrete having a 3-foot reinforced concrete roof. The bomb penetrated the roof and completely demolished the shelter.

16. **Fortifications**. Physical Damage Report 14 covers the survey of bomb damage to Fort Saint Blaise at Metz, France. At different times this tactical target was attacked by ground troops using artillery up to 250 mm; by fighter bombers dropping 250- to 1000-lb. bombs (no structural damage was apparent from these attacks by the ground forces and the fighter bombers); and, on 8 October 1944 by B-26's, dropping 2000-lb. bombs. Of these 2000-lb. bombs, six were direct hits and four were near-misses. The analysis in PDD 14 treats with damage caused by the 2000-lb. bombs and may be seen for details.

b. Heavy damage, a major part has been destroyed. Usually the machine would be returned to its manufacturer for repairs.

c. Moderate damage, a minor part has been destroyed which can be secured from the manufacturer or can be made and installed in the plant.

d. Light damage, destruction of electrical leads, or that which can be repaired by welding, etc.

Occasionally the last two of these classes are grouped together under either of the terms.

4. Sources of Information. In compiling this report slight use was made of reports by other organizations and of interrogations of German military and industrial personnel. Some facts were secured from the physical damage sections of plant reports written by other divisions of the Survey. The chief source of data, however, was the incident reports written by the division. These later record the findings of division personnel who accompanied industry teams on plant visits or, in many cases, the findings of teams which were organized and sent out by the division itself. A list of Physical Damage Division reports is attached hereto as Appendix A. For the convenience of those who may be interested, the reports are classified by industries in Appendix B.

5. Limitations of This Report. This report is an attempt to strike an average and draw some conclusions from the available data. Its weakness follows from the facts that: in many cases the source material is quite meagre; much of the material does not readily lend itself to summarization or averaging; and, of necessity, the work has been hurried. Concerning the first of the above facts, it is freely admitted that the material gathered, in spite of its seeming bulk, is but a small sample of what might have been secured with additional time and personnel. However, the group which has compiled the report sees no reason to suspect that consideration of a larger sample would have appreciably changed its conclusions. Concerning the second, even a slight acquaintance in the field with bomb damage, forces on the observer the conviction that there is enormous variation in results under essentially similar circumstances. Hence, two incidents at a single plant will defy a simple concise statement, and on occasions, observers at different plants will reach opposite conclusions. For this reason the serious student is advised to examine the individual incident reports of the division, which are believed, in general, to be of greater value than this present report.

HOW BOMBS PRODUCE DAMAGE

HE BOMBS

1. An HE bomb consists of a case, usually of steel, an explosive filling, and a fuze or fuzes. The function of the fuze is to detonate the filling at the proper time or place. The case serves one or more of several useful purposes. It protects the filling during storage and handling. It provides the confinement generally needed for high-order detonation of explosive. It permits the bomb to perforate or penetrate intact more or less resistant targets. Upon detonation it breaks up into fragments capable of doing damage.

2. An HE weapon causes damage in a number of different ways, namely, through contact explosion (combined damage effects); fragment; debris; air shock (blast), earth or water shock; and earth cratering due to destroying support or undermining. HE bombs also cause fires under certain conditions. As a secondary effect the deterioration of equipment from exposure to the elements is significant.

3. Different targets differ greatly in their vulnerability to each kind of action. For example, personnel, airplanes, light transport, lightly protected guns, and many types of machinery are vulnerable to fragmentation attack. Most buildings, except those of very heavy construction are vulnerable to air shock (blast), either interior or exterior. Very resistant structures above ground are most vulnerable to one of the following: contact explosion outside involving multiple causes of damage, interior air shock or blast, ground shock or cratering. Buried structures are vulnerable to contact or internal explosion or to earth shock.

4. Similarly, different weapons differ greatly in their ability to create each type of damage. A light cased bomb creates more blast, but generally produces fewer and lighter fragments than does a heavy cased bomb of the same weight. An AP (i.e. armor piercing) or SAP (i.e. semi-armor piercing) bomb has a comparatively small blast effect, due to the relatively small amount of explosive carried and to the confining action of its heavy case.

5. In selecting a weapon for a particular target it is desirable to match the maximum effectiveness of the former to the maximum vulnerability of the latter, subject to the requirement that perforation or penetration may have to be achieved without case failure, and to operational factors such as stowage and availability. In other words, targets that are vulnerable to blast are best attacked with bombs that create maximum blast.

6. American HE Bombs.

a. AP (Armor Piercing) bombs are used in the following sizes: 1000 lb. and 1600 lb. weight; the ratio of charge weight to total weight is about 15%. AP bombs are of small diameter and of stream lined shape, giving very high terminal velocity and also very high case strength. The filling is TNT or explosive D; fillings sensitive to shock are not suitable. This weapon is only used when perforation or penetration of extremely resistant targets (up to 5 ft. or 6 ft. of concrete

or 6-in. to 8-in. armor) is required. No nose fuze is used. Tail fuze is normally 0.08 sec. delay.

b. SAP (Semi-Armor piercing) bombs are used in the following sizes: 500 lb. and 1000 lb.; the charge weight ratio is about 30%. The slightly stream lined shape gives a high terminal velocity and the extra nose and case thickness insures high case strength. The filling was formerly Amatol, but later bombs are filled with TNT. These are normally used when considerable resistance to perforation has to be overcome (i.e. 3 ft. to 4 ft. of concrete or up to 3-in. armor). This bomb is normally fuzed only at the tail with the nose fuze hole closed by a steel plug.

c. Frag Bombs are used in the following sizes: 4 lb., 20 lb., 23 lb., 90 lb., and 260 lb. The charge weight ratio is from 10% to 15%. Except for the 4-lb. (Butterfly bomb) all of these have cylindrical cases of uniform thickness. The 90-lb. and 260-lb. bombs are wrapped with longitudinally notched heavy coil steel springs to give improved fragmentation. Fragmentation bombs are normally used with the instantaneous nose fuzes, however the proximity fuze can be used with these bombs (except the 4-lb. bomb which also can be fuzed for long delay or anti-disturbance). The 260-lb. bomb takes a non-delay tail fuze in addition to the nose fuze. Fragmentation bombs are used against personnel, planes, motor transport, light open field placements, etc., when in the open. Due to their instantaneous fuzing fragmentation bombs are not suitable for use against targets under roofs.

d. GP (General Purpose) bombs are used in the following sizes: 100 lb., 250 lb., 500 lb., 1000 lb., and 2000 lb., (larger sizes have been introduced recently). The charge weight ratio is approximately 50%. All these bombs may be fuzed both nose and tail with the usual delays, namely, instantaneous nose, non-delay tail, 0.01, 0.025, 0.1 sec. nose and tail, short and long delay. These bombs are the most used of all types. The case is heavy enough to allow perforation of fairly resistant targets (from 1 ft. to 3 ft. of concrete, depending on the bomb size). The fragmentation and blast are effective against normally constructed targets.

e. LC (Light Case) bombs are used in the following size: 4000 lb., with a charge weight ratio of 80%. It is fuzed either instantaneous or with proximity fuze since the case will not stand impact. The fragmentation is relatively ineffective. It is used only when extensive blast is desired.

7. The British series of bombs is generally similar to the American except for different designations, and some difference in sizes and construction. Normally only tail fuzes are used, however some bombs use as many as three tail fuzes.

a. The AP bomb is 2000 lb. with a charge weight ratio of 10%.

b. The SAP bombs are 250 lb. and 500 lb. with a charge weight ratio of 18%, which is materially less than the 31% of American SAP bombs.

c. The Frag. bomb is 20 lb. with a charge weight ratio of 15%.

d. The GP bombs are 40 lb., 250 lb., 500 lb., 1000 lb., 1900 lb., and 4000 lb. The charge weight ratio is 30% (Corresponds to American SAP).

e. The MC (Medium Capacity) bombs are 500 lb., 1000 lb., 4000 lb., 12000 lb., and 22000 lb. The charge weight ratio is 40% to 50% (Corresponds to American GP)

f. The HC (High Capacity) bombs are 2000 lb., 4000 lb., 8000 lb. and 12000 lb. The charge weight ratio is 66% to 75% (Corresponds to American LC).

8. Types of Damage.

a. Contact explosion. When a bomb explodes in contact, or nearly in contact, with a target several actions combine to produce the final result. Fragments from the bomb case cut up the adjacent elements of the target. Very high compressive stresses produced in the material by the blast wave cause complete disintegration near the point of detonation, and partial disintegration at greater distances. At the same time, large stresses are produced in the comparatively undamaged regions. These are propagated as stress waves to distant parts of the target and give rise to various localized damage zones at boundaries, connections, and other points of discontinuity. The effect of detonation in contact with a concrete slab illustrates this behavior. Immediately beneath the point of detonation a hole or crater is formed. Surrounding this crater is a zone of concrete that is cracked and weakened. If the slab is of the proper thickness there will be a second crater formed on the far surface of the slab due to scabbing of concrete at the surface. The concrete between these craters may or may not be unharmed, depending on the thickness of slab. For thin slabs the craters will meet, resulting in complete perforation, while a very thick slab will normally show no effect on the far side.

b. Fragmentation. This is damage produced by missiles consisting of bomb component fragments. Only GP and Fragmentation Bombs are effective producers of fragments. The light case bombs have too few and too light fragments while the AP, and to a less extent, the SAP bombs give fragments relatively large and of low velocity making the bomb generally ineffective as a fragmentation weapon. When a bomb explodes, the case breaks up into fragments varying in size from very small to several times the case thickness The fragments are not distributed uniformly about the bomb, but tend to be concentrated in one or two zones. The most important spray (the equatorial spray) coincides approximately with the equatorial plane of the bomb. More exactly, the equatorial spray is directed about 10 degrees either ahead of, or behind the equatorial plane of the bomb, depending on whether tail or nose initiation is used. Under certain conditions this difference between nose and tail initiation becomes important, as in attacking machinery housed in one-story structures. In high order detonations fragment velocities range from about 2,000 to as much as 8,000 or more ft. per second, depending on charge weight ratio and type of explosive. Tables are available for fragmentation and GP bombs, showing fragment patterns and velocities as well as densities of perforation achieved against various thicknesses of armor plate at different distances. (See Terminal Ballastic Data, Vol. I-Bombing, Office of Chief of Ordnance, August 1944).

Fragmentation is most effective against compact targets containing a large proportion of vital elements, for example, personnel, all types of

machinery, transportation equipment, airplanes, electrical devices, weapons. Such targets are usually fairly immune to any kind of shock, while the high proportion of vital elements makes most fragment hits effective.

The proper fragmentation weapon to use depends mostly on the vulnerability of the target, that is, on the amount of protection that must be perforated to produce an effective hit. The larger bombs have heavier fragments, consequently an increase in target resistance normally requires an increase in bomb size. For very "soft" targets, such as personnel or light, delicate mechanisms, the smallest fragmentation bombs, i.e. the 4 lb., and 20 lb., or 23 lb., are most efficient, weight for weight. For devices protected by a $\frac{1}{2}$ in. or more of steel plate such as armored guns, large transformers, armored cars, etc., 260-lb. Frag or 500-lb., and 1000-lb. GP bombs are most effective. The use of Frag bombs is limited to targets not under cover, since instantaneous or proximity fuzing is always used with them.

Fragmentation is not an effective means of damaging structures. For light single members (say roof purlins) fragmentation will sometimes cause enough damage to require replacement. Heavy beams or columns, wall panels, floors etc., may be scarred or perforated by fragments, but can be repaired quite easily unless they are so close to the point of detonation as to make it uncertain whether blast or fragmentation played the major role.

c. Debris. Structural members, floor and roof slabs, and rock particles may be effective damaging agents against fairly vulnerable targets such as personnel and delicate mechanisms. Such missiles are larger and slower than bomb fragments. Light machine tools in very long-span concrete roofed buildings have been found to suffer very considerably from debris.

d. Air, earth and water shock. Fundamentally, these are alike inasmuch as the effect is due to pressure transmitted to the target through the medium between it and the bomb. Air shock, or blast, is the most important, since most targets are above ground. A blast wave is characterized by a very steep front, corresponding to an instantaneous pressure rise, followed by a decrease to sub-atmospheric pressures, then a gradual return to normal. The peak pressure and the positive impulse (the impulse is the product of the time during which the pressure exceeds atmospheric multiplied by the average pressure during that interval) are the most important characteristics of the wave. For normal structures and the sizes of the bombs hitherto used, damage is generally considered to depend mainly on impulse. This conclusion, which is supported by experience, has permitted the extension of the very limited conclusions first drawn as to the damage areas of different weapons against different targets to various other combinations of targets and weapons. It is one purpose of this Survey to add to present knowledge and to correct the extrapolations that have been made.

For structures whose periods of vibration are short compared to the duration of the positive pressure phase it is probable that damage from external blast will depend mostly on the peak pressure of the wave. Due to the short durations of pressure pulses from the bombs used hitherto this situation has not yet been important; it may become important with extremely powerful bombs.

It has been shown that if damage depends only on impulses, then for external blast the efficiency of bombs increases with the bomb size of a

given type. On the other hand, if damage depends only on peak pressure it can be shown that the efficiency of bombs decrease with an increase in bomb size. Consequently for external blast, the situation appears to be the following:

(1) For small bombs an increase of size increases the area of destruction per unit weight of bombs;

(2) For large bombs an increase of size decreases the area of destruction per unit weight of bombs.

Therefore, if efficiency is measured in terms of damage per weight and if all bombs are used in the same way and employ the same explosive, there will be an optimum bomb size for each type of target. The above considerations apply only to the case of external or unconfined blast. In comparing the effects of explosion within the outside of a structure several additional factors become important. Confined explosions exert greater impulses than unconfined. Furthermore, structures are generally less resistant to internal than to external forces, being designed for the latter. On the other hand, an explosion inside a structure is less effective against neighboring structures than is an unconfined explosion at the same distance. So far as confined or internal explosions are concerned the optimum size of charge is one just big enough to create the required damage to the structure in which it detonates.

External blast is comparatively ineffective in small bombs; however, the efficiency increases with size. For external blast, case weight can be kept to a minimum, allowing most of the munition weight to be explosive, while cases of at least GP bomb thicknesses are needed for internal blast to insure penetration without case failure.

External blast is effective only against buildings of normal or less strength. External blast is not an efficient use of HE bombs against very resistant buildings or against gun emplacements, air raid shelters and the like. For these, internal blast is more effective, the effectiveness depending on the degree of confinement.

e. Earth Shock. Buried, or partly buried targets are frequently best attacked through ground shock. This is also true of those surface structures whose foundations are vulnerable.

An underground explosion causes ground movements and high pressures in the surrounding earth. Any structure in or on the ground in this vicinity must resist both effects. Very small structures move easily, consequently are less likely to be damaged, than are large structures. The distance at which damage can be expected is generally small, of the order of two or three crater radii from the explosion. Tests in the USA and Britain have shown the nature of the relation between damage, distance, and mount of explosive (See eg. NDRC Div 2, Weapon Data Sheet 6A5, Underground R/C Walls - Damage by Earth Shock).

f. Underwater Shock. This is generally similar to air blast and earth shock, For this reason, and because no examples of underwater shock have been examined by the Physical Damage Division, no further discussion is given here.

g. Cratering. A bomb exploding underground at not too great a depth will produce a crater. Any structure or other object extending over or into the crater may be caused to settle through removal of support. Cratering is especially effective against strongly framed buildings having shallow footings. It is also an important cause of damage to machines or equipment of considerable length or where alignment is important, as in shafting or in coupled machinery.

h. Fire from HE. In an appreciable number of cases HE bombs start fires. This occurs mainly where highly combustible materials, oils, gases, combustible dusts, etc. are present and are released by the bomb. Ignition may be caused by the hot gases of the explosion when detonation occurs very close to the ignitible material, as when a bomb explodes in an oil or gas container. Another cause of ignition is the overturning of stoves and heaters, shorting of electrical equipment and the like. In certain high temperature-high pressure processes (as in refineries, and synthetic oil and rubber plants) the hot liquids and gases are able to ignite spontaneously when released.

INCENDIARY BOMBS

9. Ways of Firing a Target. There are two ways in which incendiaries may fire a target. One is to ignite combustible material in the target. The second is to carry combustible material to the target in the bomb. As a practical matter, the second of these two methods is not very important. The size of incendiaries is necessarily limited. Even the largest ones now in use, or projected, do not produce a very big fire, that is, do not in themselves provide enough combustible material to cause a big fire.

In setting out, therefore, to damage a target, things in the target must be looked for to cause fire damage. Failure to understand this has sometimes led to erroneous conclusions as to the steps involved in bringing about destruction or damage.

10. Flight and Penetration. The steps in setting fire to a target with an incendiary begin with the dropping of the incendiary. It must have sufficient stability in flight to come down in such a manner that it will most effectively get into the target. This usually means going through the roof. The velocity must be sufficient to carry the bomb through the type of roofs and floors known to be in the target without deformation to prevent normal operation.

11. Finding Combustible Centers. Once having penetrated into the target building so as to operate as designed, the bomb must fall into or near some material to which it can set fire. Therefore, the way in which combustible material is distributed throughout a target is important. It determines the probability of the bomb striking sufficiently near to combustible material suitable to respond to its fire starting abilities. In dwelling houses and other buildings with wooden floors and roofs, there are a good many places where a bomb can come to rest on combustible material. In industrial plants, the floors and building structure may be fire-resistive or non-combustible. Hence, the bomb must find wooden partitions, piles of wooden boxes, such as "tote" boxes, wood finish or furniture. In some industries it may have to be initiated near or on piles of combustible stocks, such as rubber for example, or spilled flammable liquids.

Usually the kind of combustible material which would be ignited by an incendiary bomb is that which is of the order of kindling: paper, excelsior, thin pieces of wood, cardboard cartons, light furniture, draperies and the like. Heavy furniture, heavy woodwork and flooring are relatively more difficult to ignite. Many of the incendiaries so far developed cannot be counted upon to always ignite combustible material unless it is in the form of highly combustibles.

12. Chance of Igniting Combustibles. The next consideration is the chance that an incendiary bomb will ignite combustible material into which it falls. Of the various types of incendiary bombs some are necessarily more efficient in igniting a specific type target, than are others. It is not practicable to generalize about their relative fire-starting abilities, because it is necessary to consider how they will perform against a variety of wooden or other combustible surfaces. Because the combinations in which these surfaces may be arranged is infinite a very large number of variables is involved.

A small magnesium bomb (2-lb. or 4-lb.) will spurt light sparks of magnesium and thermite in its first minute of operation. Thereafter it settles down to steady burning for a period of about 3 minutes, during this period a person can approach within a few feet of the burning bomb. Obviously, only paper, thin wood and other readily combustible material can be ignited from such a fire.

The small oil bomb (6-lbs.) throws out a small mass of burning gel. In hitting a surface this breaks up into smaller masses, no one of which makes a big fire. It, too, can be closely approached and therefore is most likely to touch off only light combustibles.

The larger oil bombs (30-lbs., 100-lbs., 250 lb., and 500-lbs.) are more effective. They will affect a larger area because of the greater total amount of fuel in the bomb. As a rule they break up into small masses so that the fires they start must be in materials that take fire relatively easily.

The 30-lb. and larger bombs can be expected to ignite fairly heavy combustible material in some proportion of cases. But, even the largest of these bombs produces a relatively small fire at the beginning. If they are promptly attacked with even a 1/8 in. diameter hose stream discharging as little as 2 or 3 gallons of water a minute, there is a very good chance of controlling the fire.

13. Preliminary Fire Spread. a. Next in the steps in setting fire to a building is the development of the fire from the point where the bomb initiates fire. This depends on a chain of combustible material in the immediate vicinity of the point of the bomb incident.

b. In dwelling houses there is fairly continuous chains of combustible material. The floors and furniture will usually burn and also in some cases the wall finish.

c. In industrial plants, a great variety of factors determine whether a fire once started will spread. A few of these factors can be mentioned to show how complicated this particular part of the process is to appraise.

(1) Occupancy Combustiblity Scale. Storage rooms in industrial plants may be a good place to start. These usually offer a large amount of material, most of it combustible, covering a large percentage of the floor area. Even when the goods stored are non-combustible, such as metal parts, they are often packed in cardboard containers or wooden boxes. Often they are stored on wooden shelving. A particularly good example of a highly combustible occupancy is the store room for wooden patterns in a general machine shop. As a measure of occupancy combustibility of this type the pounds of combustible material per square foot would be a relatively high figure. Also there would be a continuous chain of combustible material over the entire floor area. If this is taken as the upper end, we can visualize other occupancies on a rough scale compared to it. Lower ranges in the scale involve less and less in pounds of combustible material per square foot, wider and wider spaces between groups of material, and a poorer and poorer chain of combustibles. On such a scale the next range will include certain assembly operations where a lot of small items are put together. Small items are often handled in combustible "tote" boxes or on crowded combustible benches. Still lower on the scale would be the heavier assembly operations such as those involved in air frame assembly.

When the machine shop and metal working occupancies are reached, the occupancy combustibility is quite low. Lowest of all will be such occupancies as boiler houses and power houses or rooms where the principal machines would be compressors, pumps, generators and the like.

The foregoing is by no means a complete catalogue of combustibility ratings. It may be seen, however, that they affect the extent to which a fire once started will spread.

(2) Spread Due to the Structure. In addition to occupancy causes, there are factors in the structure of the building affecting the likelihood that a fire once started will spread. In many industrial buildings, the only major combustible material may be a wooden roof which is often some height above the floor. An incendiary must come through the roof, land on the floor, and then ignite some combustible material on which to cause flames extensive enough to ignite the roof. Consequently the higher the roof the more difficult it is for it to be reached by a fire on the floor.

(3) Walls. Any wall tends to slow down a fire as the fire must find openings through which to spread. Another

type of wall is designed as a fire wall. This, by definition, is a wall which will stop the spread of fire. Usually it is construction of brick and is so thick and resistant to heat transfer that a complete burnout may occur on one side without sufficient heat being developed on the other to permit the ignition of combustible materials.

(4) Fire Divisions. A fire division, which is the area of a building within fire walls, limits the maximum size of an individual fire. Even though theoretically possible, complete burnout within a fire division does not always occur; first, because the arrangement of combustible material within the division may not be continuous; second, because there may be partitions, often of non-combustible material, which are not substantial enough to be considered as fire walls, but which will retard the spread of fire.

The foregoing discussion, for simplicity, has been principally in terms of single-story buildings. In multi-story buildings, the floors, if fire resistive, act as barriers to the spread of fire from floor to floor. Stairway openings and elevator shafts, however, are avenues for the spread of fire.

The spread of fire from building to building is principally a matter of space between the buildings, but much judgment is required to determine whether an air gap is sufficient to stop the spread of fire in a given case. Some of the factors to be taken into account are (1) combustibility of walls, (2) combustibility of occupancies, (3) size and intensity of the fire, (4) the area of exposed walls presented to one another, and (5) size of wall openings.

14. Types of Construction. The combustibility of the building structure is a factor which operates in conjunction with the occupancy and arrangement factors described. For convenience, the types of construction are grouped into four classes: combustible (C), non-combustible (N), fire resistive (R), and mixed construction.

a. Combustible construction includes those buildings which have a roof and sometimes walls of combustible material. The burning of the combustible portion can normally be expected to cause structural damage.

b. The non-combustible type has no significant amount of combustibile material, but the structure is damageable by fire in the contents. Examples of this are concrete, asbestos, corrugated iron, pre-cast or poured-in-place cement or gypsum supported by exposed (bare) steel. Reinforced concrete less than 2½ in. thick is also classed in this category.

c. In fire-resistive construction, there is no significant amount of combustible material in the structure and the structure will withstand all except the most intense fire. Examples are reinforced concrete where the members are 2½ in. or more thick and where there is no unprotected steel; buildings, usually multi-story, where the steel

supporting the concrete floor and roof slabs is protected by at least 2 in. of concrete covering; the Zeiss-Dywidag construction where an arch of reinforced concrete 2½ in. to 3½ in. thick is used.

d. Mixed construction includes combinations of the foregoing types. A common example is a multi-story building with reinforced concrete construction except for a combustible wood roof.

15. Engineering Appraisal of Fire Vulnerability. The appraisal of the very complicated series of steps which affect the operation of incendiaries on a target would appear at first glance a somewhat hopeless task. However, it is possible to find fire protection engineers who have had experience with exactly the factors enumerated. Many of these have inspected in excess of 1000 plants and have been trained to look for the factors mentioned above. Their advice might well be sought in selecting targets for attack by incendiaries.

HIGH EXPLOSIVE BOMB DAMAGE TO BUILDINGS AND INSTALLATIONS

1. General. This part of the report deals with HE weapons and their damaging effects upon structures and installations under the following headings:

a. Industrial type buildings.

b. Heavy structures (gun emplacements, submarine pens, fortifications, coking plants).

c. Bridges.

d. Chimneys (masonry type).

e. City areas.

2. HE bomb damage only, has been considered in the text and tabulations except in the section which covers City areas. In this part of the report, HE bomb damage includes any fire damage which was caused by the detonation of HE weapons but does not include any "Mixed" damage which could have been caused by the joint action of HE and IB weapons.

3. The material analyzed has been extracted from Physical Damage Division reports covering the results of field surveys of the various targets. Table 4 lists the Physical Damage Division reports by number and title from which the pertinent data for industrial type buildings has been taken. The report numbers and titles covering source data for other installations have been referred to in the text.

4. The attempt has been made in the report to associate the HE bomb damage effects upon buildings with the structural vulnerability classification of the structure and the weapon used. In certain of the vulnerability classifications sufficient data for an effective study are lacking and that limitation must be recognized. It will be noted that the foregoing applies only to U.S. and British bombs, principally of the 500-lb. and 1000-lb. sizes. A large bomb detonation (4000-lb. and above) invariably affects buildings of more than one structural type, due to its large near-miss radius, whereas the smaller bomb has a smaller near-miss range in causing structural damage. The smaller size bomb effects are therefore more likely to be confined to the structure directly adjacent to their points of impact. This is not true of the larger sizes of bombs and the measure of their effectiveness should be obtained from the section of the report dealing with mean areas of effectiveness of HE weapons.

HE Weapons Used.

5. The following HE weapons were used to inflict damage on industrial targets which are listed in Table 4:

7. HE Bomb Damage to Industrial Buildings. Table 4 contains a compilation of data for all damaged buildings included in the targets as listed in the Table. The buildings damaged were principally of the factory type and the various appurtenant buildings usually found in industrial plants; the structures were predominantly single-story but a number of multi-story buildings were also damaged.

Table 4 lists twenty-two (22) different targets and a summary of the HE bomb damage suffered by these objectives is given below:

No. of Targets.	Plan Area of the Damaged Bldgs. Acres.	Total Floor Area of Damaged Bldgs. Acres.	Total Area of Struct'l Roof Damage Acres	Total Area of Struct'l Floor Damage Acres.
22	217	253	83	15

Total Area of Supf'l Damage Acres	Fraction of Struct'l Roof Damage	Damaging HE Bombs Tons	Struct'l Damage (Roof plus Floor) in Acres/Ton
47.5	.38	420.3	0.23

One Ton = 2000 lbs.

Fire damage to roof structures, caused by HE bombs, was insignificant in amount but this category of damage accounted for 20.4% of the total area of floor damage listed. The difference in the amount of HE-fire damage suffered by roofs and floors was probably due to the ignition and burning of contents on the floors caused by detonation of the bombs.

8. Damage to Structural Types of Buildings caused by U.S. and British 500-lb. and 1000-lb. HE Bombs. Damage and bomb data has been lifted from the reports, listed in Table 4, referring to U.S. and British 500-lb. and 1000-lb. HE bombs, but only those items of damage which were definitely tied back to a specific weapon and to a specific structural type were extracted to avoid confusion with the effects of other weapons. Buildings of different construction have different vulnerabilities to HE bombing, in general, and a division of buildings into structural types has been made in order to compare the damage to the respective types caused by a given weapon. The structural types are indicated below:

Symbol	Description
	Single-Story Buildings
1/a	Masonry load bearing wall types
1/b	Light factory types; steel or wood framed
1/c	Heavy steel framed or those containing runways that support heavy cranes.

Symbol	Description
1/d	Hangar and Aircraft assembly types; steel, timber or reinforced concrete framed roofs
1/c	Factory reinforced concrete framed or shell types
1/f	Miscellaneous buildings of light construction.
	Multi-Story Buildings
M/a	Masonry load bearing wall types or those of composite construction
M/b	Steel framed
M/c	Reinforced concrete framed or flat slab construction.

The above structural types have been used in Table 1-3, which compare the damage effects of U.S. and British, 500-lb. and 1000-lb. bombs.

9. Table 1 separates U.S. and British bombs of the 500-lb. and 1000-lb. sizes by the fuzings used; structural roof damage, the number of bombs inflicting the damage and the structural roof damage in acres/ton is indicated for the purposes of comparison. Due attention must be given to the number of cases involved; the reliability of the values in column 10 is contingent upon the number of buildings attacked with the weapon.

a. Few cases were available for the British bombs of the 500-lb. and 1000-lb. sizes and the data for the 1/c, 1/c and 1/f structural types for the 1000-lb. MC appears to be the best.

b. U.S. 500-lb. GP - The most reliable data is shown for the 1/a, 1/b and the 1/f structural types. The 0.01 sec. tail delay fuze produced more damage per ton of HE than the 0.025 sec. tail delay fuze, except for type 1/f where the result was nearly equal. Data for the multi-story type in Table 3, are inadequate in amount for conclusions.

c. U.S. 1000-lb. GP - This weapon does not appear to be as efficient for causing damage as the 500-lb. GP, but additional incidents are required for a true evaluation. The 0.025 sec. tail fuze fitted to this weapon appears to produce more damage than the 0.01 sec. tail fuze.

d. British 500-lb. MC - Insufficient data does not permit any appraisal of this weapon to cause damage.

e. British 1000-lb. MC - the best data for this weapon is shown against the 1/c structural type where the 0.01 sec. delay fuze

seems more efficient in producing damage. Against the 1/f structural type the 0.025 delay fuze was better than non-delay but an insufficient number of cases will not support a conclusion. The 1000-lb. MC fuzed 0.025 sec. delay shows better results against the 1/c structural type than the U.S. 1000-lb. GP. fuzed 0.025 sec. tail delay.

10. Table 2 has been prepared to indicate the effect of U.S. 500-lb. and 1000-lb. GP bombs against the structural types, regardless of fuzings. Incidents have been added to those shown in Table 1 to include those buildings which were attacked with bombs fitted with mixed fuzings. . Sufficient data for accurate study are not available for the following items:

HE Weapon	Structural Type
U.S. 500-lb. GP	1/c
Br. 1000-lb. MC	1/a, 1/f.

Table 2 suggests that the U.S. 500-lb. GP is a more efficient weapon against the various structural types than the U.S. 1000-lb. GP. The British 1000-lb. MC type shows superiority over the U.S. 1000-lb. GP in attacking structures of type 1/c, but is inferior against type 1/c structures, on the basis of the data listed.

HEAVY STRUCTURES.

11. Submarine Pens. Reports 10 and 39 cover the results of bombing attacks on the submarine pens located at Brest, France, and Hamburg, Germany respectively. In both instances 12000-lb. (Tallboy) bombs, employing various fuze settings, were the weapons used in the attacks. Results of the surveys show that little effective damage was accomplished and in neither case were the pens rendered unserviceable. A description of each target and summary of damage inflicted follows:

12. Submarine Pens at Brest, France (PDD 10). This structure was constructed of reinforced concrete of excellent design and strength. It was 1200 feet long by 600 feet wide and contained 15 submarine pens. Original construction had a flat reinforced concrete roof varying in thickness from 12 ft. 8 in. to 14 ft. However the protective quality of the roof was supplemented by several methods on different roof areas. In some areas an additional 5 ft. of reinforced concrete was poured directly on the original roof without bonding by reinforcement steel. On other areas precast concrete blocks were laid, and on others a slightly pitched roof of reinforced concrete was erected. In the latter areas an air space existed between the original roof and supplementary protection. This pen received nine direct hits by 12000-lb. (Tallboy) British bombs. Five were fuzed for 11 sec. delay action and four were fuzed 0.5 sec. delay. In addition two of the same type bombs fuzed 0.5 sec. detonated near the rear side of the pen. In all direct hits the bombs failed to penetrate the roof prior to detonation. Strikes on roof spans either resulted in craters with accompanying under-roof spalling or hour-glass shaped openings. Strikes on areas directly over heavy partition walls resulted in roof craters and spalling on the underside of the roof and partition wall. In no case did serious structural damage occur such as roof collapse or wall cracking. Minor damage occurred to interior facilities such as crane rails, air and electric lines, walkways and hand rails by falling debris from the roof spalls. The two strikes at the rear of the structure caused no damage to the main building but demolished a few nearby buildings of light construction.

13. Submarine Pens at Hamburg, Germany (PDD 39) This structure was constructed of reinforced concrete of excellent design and strength. It was 518 ft. long by 442 ft. wide and had a flat reinforced concrete roof varying in thickness from 10 ft. to 11 ft. 6 in. This pen received six direct hits by 12000-lb. (Tallboy) British bombs all fuzed 25 to 30 sec. delay. In addition one near miss by the same type bomb and same fuzing occurred 100-ft. from the west sidewall of the structure. As in the cases of the strikes on the pens at Brest, France, none of the direct hits penetrated the roof prior to detonation. Crater data and interrogation of witnesses resulted in the conclusion that all bombs detonated non-delay after penetrating about 3 ft. into the roof concrete. Strikes on the roof resulted in each case, of hour-glass shaped openings ranging in lip diameter from 14 to 25 ft. and in throat diameter from 9 to 16 ft. with the minimum section occurring from 3 to 5 ft. below the roof surface. No major structural damage, such as roof collapse or fracturing, resulted from the hits. Minor damage to operating devices inside the pens resulted

from falling debris. The near miss caused settlement and lateral displacement of the west wall but did not materially effect the stability of the structure nor prevent its continued use as a submarine pen.

14. Coking Plants. Physical Damage Report 13 covered the survey of bomb damage to coking plants, located at Montigny and Liege, Belgium. In addition the Munitions Division of the Survey issued report "The Coking Industry in Germany". The interested reader will find details in these two reports.

15. Gun Emplacements. Physical Damage Division Report 1 covers the results of bombing attacks on four 15-cm gun emplacements located near Longues, France. The target consisted of an area which included not only the four separate gun emplacements but also communication tunnels and trenches, personnel shelters, ammunition storage shelters and observation posts. The area was well saturated with bomb hits which included two direct hits on structures and two near-miss hits to structures. Positive identification of the size and fuzing of the bombs was not possible but in the opinion of the survey party all strikes were made by 1,000-lb. GP bombs fuzed with 0.1 sec. nose and 0.01 sec. tail fuzes. Damage resulting from these four hits is described in the following:

a. One direct hit and two near misses occurred at Gun Emplacement 2. The direct hit struck on the roof of the left wing which, at the point of contact, was estimated to be four to five feet in thickness and was constructed of reinforced concrete. This bomb penetrated the roof and resulting blast destroyed the westwall and fractured the east interior wing wall from the ceiling to the floor. One near miss, striking three feet from the front corner of Emplacement 2, badly cracked the concrete gun base probably putting the gun out of action. Another near miss two feet from the right wing of the emplacement apparently caused no material structural damage.

b. One direct hit occurred on the roof of an ammunition storage shelter. This building was constructed of reinforced concrete having a 3-foot reinforced concrete roof. The bomb penetrated the roof and completely demolished the shelter.

16. Fortifications. Physical Damage Report 14 covers the survey of bomb damage to Fort Saint Blaise at Metz, France. At different times this tactical target was attacked by ground troops using artillery up to 250 mm; by fighter bombers dropping 250- to 1000-lb. bombs (no structural damage was apparent from these attacks by the ground forces and the fighter bombers); and, on 8 October 1944 by B-26's, dropping 2000-lb. bombs. Of these 2000-lb. bombs, six were direct hits and four were near-misses. The analysis in PDD 14 treats with damage caused by the 2000-lb. bombs and may be seen for details.

b. Heavy damage, a major part has been destroyed. Usually the machine would be returned to its manufacturer for repairs.

c. Moderate damage, a minor part has been destroyed which can be secured from the manufacturer or can be made and installed in the plant.

d. Light damage, destruction of electrical leads, or that which can be repaired by welding, etc.

Occasionally the last two of these classes are grouped together under either of the terms.

4. Sources of Information. In compiling this report slight use was made of reports by other organizations and of interrogations of German military and industrial personnel. Some facts were secured from the physical damage sections of plant reports written by other divisions of the Survey. The chief source of data, however, was the incident reports written by the division. These later record the findings of division personnel who accompanied industry teams on plant visits or, in many cases, the findings of teams which were organized and sent out by the division itself. A list of Physical Damage Division reports is attached hereto as Appendix A. For the convenience of those who may be interested, the reports are classified by industries in Appendix B.

5. Limitations of This Report. This report is an attempt to strike an average and draw some conclusions from the available data. Its weakness follows from the facts that: in many cases the source material is quite meagre; much of the material does not readily lend itself to summarization or averaging; and, of necessity, the work has been hurried. Concerning the first of the above facts, it is freely admitted that the material gathered, in spite of its seeming bulk, is but a small sample of what might have been secured with additional time and personnel. However, the group which has compiled the report sees no reason to suspect that consideration of a larger sample would have appreciably changed its conclusions. Concerning the second, even a slight acquaintance in the field with bomb damage, forces on the observer the conviction that there is enormous variation in results under essentially similar circumstances. Hence, two incidents at a single plant will defy a simple concise statement, and on occasions, observers at different plants will reach opposite conclusions. For this reason the serious student is advised to examine the individual incident reports of the division, which are believed, in general, to be of greater value than this present report.

HOW BOMBS PRODUCE DAMAGE

HE BOMBS

1. An HE bomb consists of a case, usually of steel, an explosive filling, and a fuze or fuzes. The function of the fuze is to detonate the filling at the proper time or place. The case serves one or more of several useful purposes. It protects the filling during storage and handling. It provides the confinement generally needed for high-order detonation of explosive. It permits the bomb to perforate or penetrate intact more or less resistant targets. Upon detonation it breaks up into fragments capable of doing damage.

2. An HE weapon causes damage in a number of different ways, namely, through contact explosion (combined damage effects); fragment; debris; air shock (blast), earth or water shock; and earth cratering due to destroying support or undermining. HE bombs also cause fires under certain conditions. As a secondary effect the deterioration of equipment from exposure to the elements is significant.

3. Different targets differ greatly in their vulnerability to each kind of action. For example, personnel, airplanes, light transport, lightly protected guns, and many types of machinery are vulnerable to fragmentation attack. Most buildings, except those of very heavy construction are vulnerable to air shock (blast), either interior or exterior. Very resistant structures above ground are most vulnerable to one of the following: contact explosion outside involving multiple causes of damage, interior air shock or blast, ground shock or cratering. Buried structures are vulnerable to contact or internal explosion or to earth shock.

4. Similarly, different weapons differ greatly in their ability to create each type of damage. A light cased bomb creates more blast, but generally produces fewer and lighter fragments than does a heavy cased bomb of the same weight. An AP (i.e. armor piercing) or SAP (i.e. semi-armor piercing) bomb has a comparatively small blast effect, due to the relatively small amount of explosive carried and to the confining action of its heavy case.

5. In selecting a weapon for a particular target it is desirable to match the maximum effectiveness of the former to the maximum vulnerability of the latter, subject to the requirement that perforation or penetration may have to be achieved without case failure, and to operational factors such as stowage and availability. In other words, targets that are vulnerable to blast are best attacked with bombs that create maximum blast.

6. American HE Bombs.

a. AP (Armor Piercing) bombs are used in the following sizes: 1000 lb. and 1600 lb. weight; the ratio of charge weight to total weight is about 15%. AP bombs are of small diameter and of stream lined shape, giving very high terminal velocity and also very high case strength. The filling is TNT or explosive D; fillings sensitive to shock are not suitable. This weapon is only used when perforation or penetration of extremely resistant targets (up to 5 ft. or 6 ft. of concrete

or 6-in. to 8-in. armor) is required. No nose fuze is used. Tail fuze is normally 0.08 sec. delay.

b. SAP (Semi-Armor piercing) bombs are used in the following sizes: 500 lb. and 1000 lb.; the charge weight ratio is about 30%. The slightly stream lined shape gives a high terminal velocity and the extra nose and case thickness insures high case strength. The filling was formerly Amatol, but later bombs are filled with TNT. These are normally used when considerable resistance to perforation has to be overcome (i.e. 3 ft. to 4 ft. of concrete or up to 3-in. armor). This bomb is normally fuzed only at the tail with the nose fuze hole closed by a steel plug.

c. Frag Bombs are used in the following sizes: 4 lb., 20 lb., 23 lb., 90 lb., and 260 lb. The charge weight ratio is from 10% to 15%. Except for the 4-lb. (Butterfly bomb) all of these have cylindrical cases of uniform thickness. The 90-lb. and 260-lb. bombs are wrapped with longitudinally notched heavy coil steel springs to give improved fragmentation. Fragmentation bombs are normally used with the instantaneous nose fuzes, however the proximity fuze can be used with these bombs (except the 4-lb. bomb which also can be fuzed for long delay or anti-disturbance). The 260-lb. bomb takes a non-delay tail fuze in addition to the nose fuze. Fragmentation bombs are used against personnel, planes, motor transport, light open field placements, etc., when in the open. Due to their instantaneous fuzing fragmentation bombs are not suitable for use against targets under roofs.

d. GP (General Purpose) bombs are used in the following sizes: 100 lb., 250 lb., 500 lb., 1000 lb., and 2000 lb., (larger sizes have been introduced recently). The charge weight ratio is approximately 50%. All these bombs may be fuzed both nose and tail with the usual delays, namely, instantaneous nose, non-delay tail, 0.01, 0.025, 0.1 sec. nose and tail, short and long delay. These bombs are the most used of all types. The case is heavy enough to allow perforation of fairly resistant targets (from 1 ft. to 3 ft. of concrete, depending on the bomb size). The fragmentation and blast are effective against normally constructed targets.

e. LC (Light Case) bombs are used in the following size: 4000 lb., with a charge weight ratio of 80%. It is fuzed either instantaneous or with proximity fuze since the case will not stand impact. The fragmentation is relatively ineffective. It is used only when extensive blast is desired.

7. The British series of bombs is generally similar to the American except for different designations, and some difference in sizes and construction. Normally only tail fuzes are used, however some bombs use as many as three tail fuzes.

a. The AP bomb is 2000 lb. with a charge weight ratio of 10%.

b. The SAP bombs are 250 lb. and 500 lb. with a charge weight ratio of 18%, which is materially less than the 31% of American SAP bombs.

c. The Frag. bomb is 20 lb. with a charge weight ratio of 15%.

d. The GP bombs are 40 lb., 250 lb., 500 lb., 1000 lb., 1900 lb., and 4000 lb. The charge weight ratio is 30% (Corresponds to American SAP).

e. The MC (Medium Capacity) bombs are 500 lb., 1000 lb., 4000 lb., 12000 lb., and 22000 lb. The charge weight ratio is 40% to 50% (Corresponds to American GP)

f. The HC (High Capacity) bombs are 2000 lb., 4000 lb., 8000 lb. and 12000 lb. The charge weight ratio is 66% to 75% (Corresponds to American LC).

8. Types of Damage.

a. Contact explosion. When a bomb explodes in contact, or nearly in contact, with a target several actions combine to produce the final result. Fragments from the bomb case cut up the adjacent elements of the target. Very high compressive stresses produced in the material by the blast wave cause complete disintegration near the point of detonation, and partial disintegration at greater distances. At the same time, large stresses are produced in the comparatively undamaged regions. These are propagated as stress waves to distant parts of the target and give rise to various localized damage zones at boundaries, connections, and other points of discontinuity. The effect of detonation in contact with a concrete slab illustrates this behavior. Immediately beneath the point of detonation a hole or crater is formed. Surrounding this crater is a zone of concrete that is cracked and weakened. If the slab is of the proper thickness there will be a second crater formed on the far surface of the slab due to scabbing of concrete at the surface. The concrete between these craters may or may not be unharmed, depending on the thickness of slab. For thin slabs the craters will meet, resulting in complete perforation, while a very thick slab will normally show no effect on the far side.

b. Fragmentation. This is damage produced by missiles consisting of bomb component fragments. Only GP and Fragmentation Bombs are effective producers of fragments. The light case bombs have too few and too light fragments while the AP, and to a less extent, the SAP bombs give fragments relatively large and of low velocity making the bomb generally ineffective as a fragmentation weapon. When a bomb explodes, the case breaks up into fragments varying in size from very small to several times the case thickness The fragments are not distributed uniformly about the bomb, but tend to be concentrated in one or two zones. The most important spray (the equatorial spray) coincides approximately with the equatorial plane of the bomb. More exactly, the equatorial spray is directed about 10 degrees either ahead of, or behind the equatorial plane of the bomb, depending on whether tail or nose initiation is used. Under certain conditions this difference between nose and tail initiation becomes important, as in attacking machinery housed in one-story structures. In high order detonations fragment velocities range from about 2,000 to as much as 8,000 or more ft. per second, depending on charge weight ratio and type of explosive. Tables are available for fragmentation and GP bombs, showing fragment patterns and velocities as well as densities of perforation achieved against various thicknesses of armor plate at different distances. (See Terminal Ballastic Data, Vol. I-Bombing, Office of Chief of Ordnance, August 1944).

Fragmentation is most effective against compact targets containing a large proportion of vital elements, for example, personnel, all types of

machinery, transportation equipment, airplanes, electrical devices, weapons. Such targets are usually fairly immune to any kind of shock, while the high proportion of vital elements makes most fragment hits effective.

The proper fragmentation weapon to use depends mostly on the vulnerability of the target, that is, on the amount of protection that must be perforated to produce an effective hit. The larger bombs have heavier fragments, consequently an increase in target resistance normally requires an increase in bomb size. For very "soft" targets, such as personnel or light, delicate mechanisms, the smallest fragmentation bombs, i.e. the 4 lb., and 20 lb., or 23 lb., are most efficient, weight for weight. For devices protected by a $\frac{1}{2}$ in. or more of steel plate such as armored guns, large transformers, armored cars, etc., 260-lb. Frag or 500-lb., and 1000-lb. GP bombs are most effective. The use of Frag bombs is limited to targets not under cover, since instantaneous or proximity fuzing is always used with them.

Fragmentation is not an effective means of damaging structures. For light single members (say roof purlins) fragmentation will sometimes cause enough damage to require replacement. Heavy beams or columns, wall panels, floors etc., may be scarred or perforated by fragments, but can be repaired quite easily unless they are so close to the point of detonation as to make it uncertain whether blast or fragmentation played the major role.

c. <u>Debris.</u> Structural members, floor and roof slabs, and rock particles may be effective damaging agents against fairly vulnerable targets such as personnel and delicate mechanisms. Such missiles are larger and slower than bomb fragments. Light machine tools in very long-span concrete roofed buildings have been found to suffer very considerably from debris.

d. <u>Air, earth and water shock.</u> Fundamentally, these are alike inasmuch as the effect is due to pressure transmitted to the target through the medium between it and the bomb. Air shock, or blast, is the most important, since most targets are above ground. A blast wave is characterized by a very steep front, corresponding to an instantaneous pressure rise, followed by a decrease to sub-atmospheric pressures, then a gradual return to normal. The peak pressure and the positive impulse (the impulse is the product of the time during which the pressure exceeds atmospheric multiplied by the average pressure during that interval) are the most important characteristics of the wave. For normal structures and the sizes of the bombs hitherto used, damage is generally considered to depend mainly on impulse. This conclusion, which is supported by experience, has permitted the extension of the very limited conclusions first drawn as to the damage areas of different weapons against different targets to various other combinations of targets and weapons. It is one purpose of this Survey to add to present knowledge and to correct the extrapolations that have been made.

For structures whose periods of vibration are short compared to the duration of the positive pressure phase it is probable that damage from external blast will depend mostly on the peak pressure of the wave. Due to the short durations of pressure pulses from the bombs used hitherto this situation has not yet been important; it may become important with extremely powerful bombs.

It has been shown that if damage depends only on impulses, then for external blast the efficiency of bombs increases with the bomb size of a

given type. On the other hand, if damage depends only on <u>peak pressure</u> it can be shown that the efficiency of bombs decrease with an increase in bomb size. Consequently for external blast, the situation appears to be the following:

(1) For small bombs an increase of size increases the area of destruction per unit weight of bombs;

(2) For large bombs an increase of size decreases the area of destruction per unit weight of bombs.

Therefore, if efficiency is measured in terms of damage per weight and if all bombs are used in the same way and employ the same explosive, there will be an optimum bomb size for each type of target. The above considerations apply only to the case of external or unconfined blast. In comparing the effects of explosion within the outside of a structure several additional factors become important. Confined explosions exert greater impulses than unconfined. Furthermore, structures are generally less resistant to internal than to external forces, being designed for the latter. On the other hand, an explosion inside a structure is less effective against neighboring structures than is an unconfined explosion at the same distance. So far as confined or internal explosions are concerned the optimum size of charge is one just big enough to create the required damage to the structure in which it detonates.

External blast is comparatively ineffective in small bombs; however, the efficiency increases with size. For external blast, case weight can be kept to a minimum, allowing most of the munition weight to be explosive, while cases of at least GP bomb thicknesses are needed for internal blast to insure penetration without case failure.

External blast is effective only against buildings of normal or less strength. External blast is not an efficient use of HE bombs against very resistant buildings or against gun emplacements, air raid shelters and the like. For these, internal blast is more effective, the effectiveness depending on the degree of confinement.

e. <u>Earth Shock.</u> Buried, or partly buried targets are frequently best attacked through ground shock. This is also true of those surface structures whose foundations are vulnerable.

An underground explosion causes ground movements and high pressures in the surrounding earth. Any structure in or on the ground in this vicinity must resist both effects. Very small structures move easily, consequently are less likely to be damaged, than are large structures. The distance at which damage can be expected is generally small, of the order of two or three crater radii from the explosion. Tests in the USA and Britain have shown the nature of the relation between damage, distance, and mount of explosive (See eg. NDRC Div 2, Weapon Data Sheet 6A5, <u>Underground R/C Walls - Damage by Earth Shock</u>).

f. <u>Underwater Shock.</u> This is generally similar to air blast and earth shock. For this reason, and because no examples of underwater shock have been examined by the Physical Damage Division, no further discussion is given here.

g. Cratering. A bomb exploding underground at not too great a depth will produce a crater. Any structure or other object extending over or into the crater may be caused to settle through removal of support. Cratering is especially effective against strongly framed buildings having shallow footings. It is also an important cause of damage to machines or equipment of considerable length or where alignment is important, as in shafting or in coupled machinery.

h. Fire from HE. In an appreciable number of cases HE bombs start fires. This occurs mainly where highly combustible materials, oils, gases, combustible dusts, etc. are present and are released by the bomb. Ignition may be caused by the hot gases of the explosion when detonation occurs very close to the ignitible material, as when a bomb explodes in an oil or gas container. Another cause of ignition is the overturning of stoves and heaters, shorting of electrical equipment and the like. In certain high temperature-high pressure processes (as in refineries, and synthetic oil and rubber plants) the hot liquids and gases are able to ignite spontaneously when released.

INCENDIARY BOMBS

9. Ways of Firing a Target. There are two ways in which incendiaries may fire a target. One is to ignite combustible material in the target. The second is to carry combustible material to the target in the bomb. As a practical matter, the second of these two methods is not very important. The size of incendiaries is necessarily limited. Even the largest ones now in use, or projected, do not produce a very big fire, that is, do not in themselves provide enough combustible material to cause a big fire.

In setting out, therefore, to damage a target, things in the target must be looked for to cause fire damage.. Failure to understand this has sometimes led to erroneous conclusions as to the steps involved in bringing about destruction or damage.

10. Flight and Penetration. The steps in setting fire to a target with an incendiary begin with the dropping of the incendiary. It must have sufficient stability in flight to come down in such a manner that it will most effectively get into the target. This usually means going through the roof. The velocity must be sufficient to carry the bomb through the type of roofs and floors known to be in the target without deformation to prevent normal operation.

11. Finding Combustible Centers. Once having penetrated into the target building so as to operate as designed, the bomb must fall into or near some material to which it can set fire. Therefore, the way in which combustible material is distributed throughout a target is important. It determines the probability of the bomb striking sufficiently near to combustible material suitable to respond to its fire starting abilities. In dwelling houses and other buildings with wooden floors and roofs, there are a good many places where a bomb can come to rest on combustible material. In industrial plants, the floors and building structure may be fire-resistive or non-combustible. Hence, the bomb must find wooden partitions, piles of wooden boxes, such as "tote" boxes, wood finish or furniture. In some industries it may have to be initiated near or on piles of combustible stocks, such as rubber for example, or spilled flammable liquids.

Usually the kind of combustible material which would be ignited by an incendiary bomb is that which is of the order of kindling: paper, excelsior, thin pieces of wood, cardboard cartons, light furniture, draperies and the like. Heavy furniture, heavy woodwork and flooring are relatively more difficult to ignite. Many of the incendiaries so far developed cannot be counted upon to always ignite combustible material unless it is in the form of highly combustibles.

12. Chance of Igniting Combustibles. The next consideration is the chance that an incendiary bomb will ignite combustible material into which it falls. Of the various types of incendiary bombs some are necessarily more efficient in igniting a specific type target, than are others. It is not practicable to generalize about their relative fire-starting abilities, because it is necessary to consider how they will perform against a variety of wooden or other combustible surfaces. Because the combinations in which these surfaces may be arranged is infinite a very large number of variables is involved.

A small magnesium bomb (2-lb. or 4-lb.) will spurt light sparks of magnesium and thermite in its first minute of operation. Thereafter it settles down to steady burning for a period of about 3 minutes, during this period a person can approach within a few feet of the burning bomb. Obviously, only paper, thin wood and other readily combustible material can be ignited from such a fire.

The small oil bomb (6-lbs.) throws out a small mass of burning gel. In hitting a surface this breaks up into smaller masses, no one of which makes a big fire. It, too, can be closely approached and therefore is most likely to touch off only light combustibles.

The larger oil bombs (30-lbs., 100-lbs., 250 lb. and 500-lbs.) are more effective. They will affect a larger area because of the greater total amount of fuel in the bomb. As a rule they break up into small masses so that the fires they start must be in materials that take fire relatively easily.

The 30-lb. and larger bombs can be expected to ignite fairly heavy combustible material in some proportion of cases. But, even the largest of these bombs produces a relatively small fire at the beginning. If they are promptly attacked with even a 1/8 in. diameter hose stream discharging as little as 2 or 3 gallons of water a minute, there is a very good chance of controlling the fire.

13. Preliminary Fire Spread. a. Next in the steps in setting fire to a building is the development of the fire from the point where the bomb initiates fire. This depends on a chain of combustible material in the immediate vicinity of the point of the bomb incident.

b. In dwelling houses there is fairly continuous chains of combustible material. The floors and furniture will usually burn and also in some cases the wall finish.

c. In industrial plants, a great variety of factors determine whether a fire once started will spread. A few of these factors can be mentioned to show how complicated this particular part of the process is to appraise.

(1) Occupancy Combustiblity Scale. Storage rooms in industrial plants may be a good place to start. These usually offer a large amount of material, most of it combustible, covering a large percentage of the floor area. Even when the goods stored are non-combustible, such as metal parts, they are often packed in cardboard containers or wooden boxes. Often they are stored on wooden shelving. A particularly good example of a highly combustible occupancy is the store room for wooden patterns in a general machine shop. As a measure of occupancy combustibility of this type the pounds of combustible material per square foot would be a relatively high figure. Also there would be a continuous chain of combustible material over the entire floor area. If this is taken as the upper end, we can visualize other occupancies on a rough scale compared to it. Lower ranges in the scale involve less and less in pounds of combustible material per square foot, wider and wider spaces between groups of material, and a poorer and poorer chain of combustibles. On such a scale the next range will include certain assembly operations where a lot of small items are put together. Small items are often handled in combustible "tote" boxes or on crowded combustible benches. Still lower on the scale would be the heavier assembly operations such as those involved in air frame assembly.

When the machine shop and metal working occupancies are reached, the occupancy combustibility is quite low. Lowest of all will be such occupancies as boiler houses and power houses or rooms where the principal machines would be compressors, pumps, generators and the like.

The foregoing is by no means a complete catalogue of combustibility ratings. It may be seen, however, that they affect the extent to which a fire once started will spread.

(2) Spread Due to the Structure. In addition to occupancy causes, there are factors in the structure of the building affecting the likelihood that a fire once started will spread. In many industrial buildings, the only major combustible material may be a wooden roof which is often some height above the floor. An incendiary must come through the roof, land on the floor, and then ignite some combustible material on which to cause flames extensive enough to ignite the roof. Consequently the higher the roof the more difficult it is for it to be reached by a fire on the floor.

(3) Walls. Any wall tends to slow down a fire as the fire must find openings through which to spread. Another

type of wall is designed as a fire wall. This, by definition, is a wall which will stop the spread of fire. Usually it is construction of brick and is so thick and resistant to heat transfer that a complete burnout may occur on one side without sufficient heat being developed on the other to permit the ignition of combustible materials.

(4) Fire Divisions. A fire division, which is the area of a building within fire walls, limits the maximum size of an individual fire. Even though theoretically possible, complete burnout within a fire division does not always occur; first, because the arrangement of combustible material within the division may not be continuous; second, because there may be partitions, often of non-combustible material, which are not substantial enough to be considered as fire walls, but which will retard the spread of fire.

The foregoing discussion, for simplicity, has been principally in terms of single-story buildings. In multi-story buildings, the floors, if fire resistive, act as barriers to the spread of fire from floor to floor. Stairway openings and elevator shafts, however, are avenues for the spread of fire.

The spread of fire from building to building is principally a matter of space between the buildings, but much judgment is required to determine whether an air gap is sufficient to stop the spread of fire in a given case. Some of the factors to be taken into account are (1) combustibility of walls, (2) combustibility of occupancies, (3) size and intensity of the fire, (4) the area of exposed walls presented to one another, and (5) size of wall openings.

14. Types of Construction. The combustibility of the building structure is a factor which operates in conjunction with the occupancy and arrangement factors described. For convenience, the types of construction are grouped into four classes: combustible (C), non-combustible (N), fire resistive (R), and mixed construction.

a. Combustible construction includes those buildings which have a roof and sometimes walls of combustible material. The burning of the combustible portion can normally be expected to cause structural damage.

b. The non-combustible type has no significant amount of combustibile material, but the structure is damageable by fire in the contents Examples of this are concrete, asbestos, corrugated iron, pre-cast or poured-in-place cement or gypsum supported by exposed (bare) steel. Reinforced concrete less than 2½ in. thick is also classed in this category.

c. In fire-resistive construction, there is no significant amount of combustible material in the structure and the structure will withstand all except the most intense fire. Examples are reinforced concrete where the members are 2½ in. or more thick and where there is no unprotected steel; buildings, usually multi-story, where the steel

supporting the concrete floor and roof slabs is protected by at least 2 in. of concrete covering; the Zeiss-Dywidag construction where an arch of reinforced concrete $2\frac{1}{2}$ in. to $3\frac{1}{2}$ in. thick is used.

d. Mixed construction includes combinations of the foregoing types. A common example is a multi-story building with reinforced concrete construction except for a combustible wood roof.

15. Engineering Appraisal of Fire Vulnerability. The appraisal of the very complicated series of steps which affect the operation of incendiaries on a target would appear at first glance a somewhat hopeless task. However, it is possible to find fire protection engineers who have had experience with exactly the factors enumerated. Many of these have inspected in excess of 1000 plants and have been trained to look for the factors mentioned above. Their advice might well be sought in selecting targets for attack by incendiaries.

HIGH EXPLOSIVE BOMB DAMAGE TO BUILDINGS AND INSTALLATIONS

1. General. This part of the report deals with HE weapons and their damaging effects upon structures and installations under the following headings:

a. Industrial type buildings.

b. Heavy structures (gun emplacements, submarine pens, fortifications, coking plants).

c. Bridges.

d. Chimneys (masonry type).

e. City areas.

2. HE bomb damage only, has been considered in the text and tabulations except in the section which covers City areas. In this part of the report, HE bomb damage includes any fire damage which was caused by the detonation of HE weapons but does not include any "Mixed" damage which could have been caused by the joint action of HE and IB weapons.

3. The material analyzed has been extracted from Physical Damage Division reports covering the results of field surveys of the various targets. Table 4 lists the Physical Damage Division reports by number and title from which the pertinent data for industrial type buildings has been taken. The report numbers and titles covering source data for other installations have been referred to in the text.

4. The attempt has been made in the report to associate the HE bomb damage effects upon buildings with the structural vulnerability classification of the structure and the weapon used. In certain of the vulnerability classifications sufficient data for an effective study are lacking and that limitation must be recognized. It will be noted that the foregoing applies only to U.S. and British bombs, principally of the 500-lb. and 1000-lb. sizes. A large bomb detonation (4000-lb. and above) invariably affects buildings of more than one structural type, due to its large near-miss radius, whereas the smaller bomb has a smaller near-miss range in causing structural damage. The smaller size bomb effects are therefore more likely to be confined to the structure directly adjacent to their points of impact. This is not true of the larger sizes of bombs and the measure of their effectiveness should be obtained from the section of the report dealing with mean areas of effectiveness of HE weapons.

HE Weapons Used.

5. The following HE weapons were used to inflict damage on industrial targets which are listed in Table 4:

7. HE Bomb Damage to Industrial Buildings. Table 4 contains a compilation of data for all damaged buildings included in the targets as listed in the Table. The buildings damaged were principally of the factory type and the various appurtenant buildings usually found in industrial plants; the structures were predominantly single-story but a number of multi-story buildings were also damaged.

Table 4 lists twenty-two (22) different targets and a summary of the HE bomb damage suffered by these objectives is given below:

No. of Targets.	Plan Area of the Damaged Bldgs. Acres.	Total Floor Area of Damaged Bldgs. Acres.	Total Area of Struct'l Roof Damage Acres	Total Area of Struct'l Floor Damage Acres.
22	217	253	83	15

Total Area of Supf'l Damage Acres	Fraction of Struct'l Roof Damage	Damaging HE Bombs Tons	Struct'l Damage (Roof plus Floor) in Acres/Ton
47.5	.38	420.3	0.23

One Ton = 2000 lbs.

Fire damage to roof structures, caused by HE bombs, was insignificant in amount but this category of damage accounted for 20.4% of the total area of floor damage listed. The difference in the amount of HE-fire damage suffered by roofs and floors was probably due to the ignition and burning of contents on the floors caused by detonation of the bombs.

8. Damage to Structural Types of Buildings caused by U.S. and British 500-lb. and 1000-lb. HE Bombs. Damage and bomb data has been lifted from the reports, listed in Table 4, referring to U.S. and British 500-lb. and 1000-lb. HE bombs, but only those items of damage which were definitely tied back to a specific weapon and to a specific structural type were extracted to avoid confusion with the effects of other weapons. Buildings of different construction have different vulnerabilities to HE bombing, in general, and a division of buildings into structural types has been made in order to compare the damage to the respective types caused by a given weapon. The structural types are indicated below:

Symbol	Description
	Single-Story Buildings
1/a	Masonry load bearing wall types
1/b	Light factory types; steel or wood framed
1/c	Heavy steel framed or those containing runways that support heavy cranes.

Symbol	Description
1/d	Hangar and Aircraft assembly types; steel, timber or reinforced concrete framed roofs
1/c	Factory reinforced concrete framed or shell types
1/f	Miscellaneous buildings of light construction.
	Multi-Story Buildings
M/a	Masonry load bearing wall types or those of composite construction
M/b	Steel framed
M/c	Reinforced concrete framed or flat slab construction.

The above structural types have been used in Table 1-3, which compare the damage effects of U.S. and British, 500-lb. and 1000-lb. bombs.

9. Table 1 separates U.S. and British bombs of the 500-lb. and 1000-lb. sizes by the fuzings used; structural roof damage, the number of bombs inflicting the damage and the structural roof damage in acres/ton is indicated for the purposes of comparison. Due attention must be given to the number of cases involved; the reliability of the values in column 10 is contingent upon the number of buildings attacked with the weapon.

a. Few cases were available for the British bombs of the 500-lb. and 1000-lb. sizes and the data for the 1/c, 1/e and 1/f structural types for the 1000-lb. MC appears to be the best.-

b. U.S. 500-lb. GP - The most reliable data is shown for the 1/a, 1/b and the 1/f structural types. The 0.01 sec. tail delay fuze produced more damage per ton of HE than the 0.025 sec. tail delay fuze, except for type 1/f where the result was nearly equal. Data for the multi-story type in Table 3, are inadequate in amount for conclusions.

c. U.S. 1000-lb. GP - This weapon does not appear to be as efficient for causing damage as the 500-lb. GP, but additional incidents are required for a true evaluation. The 0.025 sec. tail fuze fitted to this weapon appears to produce more damage than the 0.01 sec. tail fuze.

d. British 500-lb. MC - Insufficient data does not permit any appraisal of this weapon to cause damage.

e. British 1000-lb. MC - the best data for this weapon is shown against the 1/c structural type where the 0.01 sec. delay fuze

seems more efficient in producing damage. Against the 1/f structural type the 0.025 delay fuze was better than non-delay but an insufficient number of cases will not support a conclusion. The 1000-lb. MC fuzed 0.025 sec. delay shows better results against the 1/c structural type than the U.S. 1000-lb. GP. fuzed 0.025 sec. tail delay.

10. Table 2 has been prepared to indicate the effect of U.S. 500-lb. and 1000-lb. GP bombs against the structural types, regardless of fuzings. Incidents have been added to those shown in Table 1 to include those buildings which were attacked with bombs fitted with mixed fuzings. Sufficient data for accurate study are not available for the following items:

HE Weapon	Structural Type
U.S. 500-lb. GP	1/c
Br. 1000-lb. MC	1/a, 1/f.

Table 2 suggests that the U.S. 500-lb. GP is a more efficient weapon against the various structural types than the U.S. 1000-lb. GP. The British 1000-lb. MC type shows superiority over the U.S. 1000-lb. GP in attacking structures of type 1/c, but is inferior against type 1/c structures, on the basis of the data listed.

HEAVY STRUCTURES.

11. Submarine Pens. Reports 10 and 39 cover the results of bombing attacks on the submarine pens located at Brest, France, and Hamburg, Germany respectively. In both instances 12000-lb. (Tallboy) bombs, employing various fuze settings, were the weapons used in the attacks. Results of the surveys show that little effective damage was accomplished and in neither case were the pens rendered unserviceable. A description of each target and summary of damage inflicted follows:

12. Submarine Pens at Brest, France (PDD 10). This structure was constructed of reinforced concrete of excellent design and strength. It was 1200 feet long by 600 feet wide and contained 15 submarine pens. Original construction had a flat reinforced concrete roof varying in thickness from 12 ft. 8 in. to 14 ft. However the protective quality of the roof was supplemented by several methods on different roof areas. In some areas an additional 5 ft. of reinforced concrete was poured directly on the original roof without bonding by reinforcement steel. On other areas precast concrete blocks were laid, and on others a slightly pitched roof of reinforced concrete was erected. In the latter areas an air space existed between the original roof and supplementary protection. This pen received nine direct hits by 12000-lb. (Tallboy) British bombs. Five were fuzed for 11 sec. delay action and four were fuzed 0.5 sec. delay. In addition two of the same type bombs fuzed 0.5 sec. detonated near the rear side of the pen. In all direct hits the bombs failed to penetrate the roof prior to detonation. Strikes on roof spans either resulted in craters with accompanying under-roof spalling or hour-glass shaped openings. Strikes on areas directly over heavy partition walls resulted in roof craters and spalling on the underside of the roof and partition wall. In no case did serious structural damage occur such as roof collapse or wall cracking. Minor damage occurred to interior facilities such as crane rails, air and electric lines, walkways and hand rails by falling debris from the roof spalls. The two strikes at the rear of the structure caused no damage to the main building but demolished a few nearby buildings of light construction.

13. Submarine Pens at Hamburg, Germany (PDD 39) This structure was constructed of reinforced concrete of excellent design and strength. It was 518 ft. long by 442 ft. wide and had a flat reinforced concrete roof varying in thickness from 10 ft. to 11 ft. 6 in. This pen received six direct hits by 12000-lb. (Tallboy) British bombs all fuzed 25 to 30 sec. delay. In addition one near miss by the same type bomb and same fuzing occurred 100-ft. from the west sidewall of the structure. As in the cases of the strikes on the pens at Brest, France, none of the direct hits penetrated the roof prior to detonation. Crater data and interrogation of witnesses resulted in the conclusion that all bombs detonated non-delay after penetrating about 3 ft. into the roof concrete. Strikes on the roof resulted in each case, of hour-glass shaped openings ranging in lip diameter from 14 to 25 ft. and in throat diameter from 9 to 16 ft. with the minimum section occurring from 3 to 5 ft. below the roof surface. No major structural damage, such as roof collapse or fracturing, resulted from the hits. Minor damage to operating devices inside the pens resulted

from falling debris. The near miss caused settlement and lateral displacement of the west wall but did not materially effect the stability of the structure nor prevent its continued use as a submarine pen.

14. Coking Plants. Physical Damage Report 13 covered the survey of bomb damage to coking plants, located at Montigny and Liege, Belgium. In addition the Munitions Division of the Survey issued report "The Coking Industry in Germany". The interested reader will find details in these two reports.

15. Gun Emplacements. Physical Damage Division Report 1 covers the results of bombing attacks on four 15-cm gun emplacements located near Longues, France. The target consisted of an area which included not only the four separate gun emplacements but also communication tunnels and trenches, personnel shelters, ammunition storage shelters and observation posts. The area was well saturated with bomb hits which included two direct hits on structures and two near-miss hits to structures. Positive identification of the size and fuzing of the bombs was not possible but in the opinion of the survey party all strikes were made by 1,000-lb. GP bombs fuzed with 0.1 sec. nose and 0.01 sec. tail fuzes. Damage resulting from these four hits is described in the following:

a. One direct hit and two near misses occurred at Gun Emplacement 2. The direct hit struck on the roof of the left wing which, at the point of contact, was estimated to be four to five feet in thickness and was constructed of reinforced concrete. This bomb penetrated the roof and resulting blast destroyed the westwall and fractured the east interior wing wall from the ceiling to the floor. One near miss, striking three feet from the front corner of Emplacement 2, badly cracked the concrete gun base probably putting the gun out of action. Another near miss two feet from the right wing of the emplacement apparently caused no material structural damage.

b. One direct hit occurred on the roof of an ammunition storage shelter. This building was constructed of reinforced concrete having a 3-foot reinforced concrete roof. The bomb penetrated the roof and completely demolished the shelter.

16. Fortifications. Physical Damage Report 14 covers the survey of bomb damage to Fort Saint Blaise at Metz, France. At different times this tactical target was attacked by ground troops using artillery up to 250 mm; by fighter bombers dropping 250- to 1000-lb. bombs (no structural damage was apparent from these attacks by the ground forces and the fighter bombers); and, on 8 October 1944 by B-26's, dropping 2000-lb. bombs. Of these 2000-lb. bombs, six were direct hits and four were near-misses. The analysis in PDD 14 treats with damage caused by the 2000-lb. bombs and may be seen for details.

b. Heavy damage, a major part has been destroyed. Usually the machine would be returned to its manufacturer for repairs.

c. Moderate damage, a minor part has been destroyed which can be secured from the manufacturer or can be made and installed in the plant.

d. Light damage, destruction of electrical leads, or that which can be repaired by welding, etc.

Occasionally the last two of these classes are grouped together under either of the terms.

4. Sources of Information. In compiling this report slight use was made of reports by other organizations and of interrogations of German military and industrial personnel. Some facts were secured from the physical damage sections of plant reports written by other divisions of the Survey. The chief source of data, however, was the incident reports written by the division. These later record the findings of division personnel who accompanied industry teams on plant visits or, in many cases, the findings of teams which were organized and sent out by the division itself. A list of Physical Damage Division reports is attached hereto as Appendix A. For the convenience of those who may be interested, the reports are classified by industries in Appendix B.

5. Limitations of This Report. This report is an attempt to strike an average and draw some conclusions from the available data. Its weakness follows from the facts that: in many cases the source material is quite meagre; much of the material does not readily lend itself to summarization or averaging; and, of necessity, the work has been hurried. Concerning the first of the above facts, it is freely admitted that the material gathered, in spite of its seeming bulk, is but a small sample of what might have been secured with additional time and personnel. However, the group which has compiled the report sees no reason to suspect that consideration of a larger sample would have appreciably changed its conclusions. Concerning the second, even a slight acquaintance in the field with bomb damage, forces on the observer the conviction that there is enormous variation in results under essentially similar circumstances. Hence, two incidents at a single plant will defy a simple concise statement, and on occasions, observers at different plants will reach opposite conclusions. For this reason the serious student is advised to examine the individual incident reports of the division, which are believed, in general, to be of greater value than this present report.

HOW BOMBS PRODUCE DAMAGE

HE BOMBS

1. An HE bomb consists of a case, usually of steel, an explosive filling, and a fuze or fuzes. The function of the fuze is to detonate the filling at the proper time or place. The case serves one or more of several useful purposes. It protects the filling during storage and handling. It provides the confinement generally needed for high-order detonation of explosive. It permits the bomb to perforate or penetrate intact more or less resistant targets. Upon detonation it breaks up into fragments capable of doing damage.

2. An HE weapon causes damage in a number of different ways, namely, through contact explosion (combined damage effects); fragment; debris; air shock (blast), earth or water shock; and earth cratering due to destroying support or underrnining. HE bombs also cause fires under certain conditions. As a secondary effect the deterioration of equipment from exposure to the elements is significant.

3. Different targets differ greatly in their vulnerability to each kind of action. For example, personnel, airplanes, light transport, lightly protected guns, and many types of machinery are vulnerable to fragmentation attack. Most buildings, except those of very heavy construction are vulnerable to air shock (blast), either interior or exterior. Very resistant structures above ground are most vulnerable to one of the following: contact explosion outside involving multiple causes of damage, interior air shock or blast, ground shock or cratering. Buried structures are vulnerable to contact or internal explosion or to earth shock.

4. Similarly, different weapons differ greatly in their ability to create each type of damage. A light cased bomb creates more blast, but generally produces fewer and lighter fragments than does a heavy cased bomb of the same weight. An AP (i.e. armor piercing) or SAP (i.e. semi-armor piercing) bomb has a comparatively small blast effect, due to the relatively small amount of explosive carried and to the confining action of its heavy case.

5. In selecting a weapon for a particular target it is desirable to match the maximum effectiveness of the former to the maximum vulnerability of the latter, subject to the requirement that perforation or penetration may have to be achieved without case failure, and to operational factors such as stowage and availability. In other words, targets that are vulnerable to blast are best attacked with bombs that create maximum blast.

6. American HE Bombs.

a. AP (Armor Piercing) bombs are used in the following sizes: 1000 lb. and 1600 lb. weight; the ratio of charge weight to total weight is about 15%. AP bombs are of small diameter and of stream lined shape, giving very high terminal velocity and also very high case strength. The filling is TNT or explosive D; fillings sensitive to shock are not suitable. This weapon is only used when perforation or penetration of extremely resistant targets (up to 5 ft. or 6 ft. of concrete

or 6-in. to 8-in. armor) is required. No nose fuze is used. Tail fuze is normally 0.08 sec. delay.

b. SAP (Semi-Armor piercing) bombs are used in the following sizes: 500 lb. and 1000 lb.; the charge weight ratio is about 30%. The slightly stream lined shape gives a high terminal velocity and the extra nose and case thickness insures high case strength. The filling was formerly Amatol, but later bombs are filled with TNT. These are normally used when considerable resistance to perforation has to be overcome (i.e. 3 ft. to 4 ft. of concrete or up to 3-in. armor). This bomb is normally fuzed only at the tail with the nose fuze hole closed by a steel plug.

c. Frag Bombs are used in the following sizes: 4 lb., 20 lb., 23 lb., 90 lb., and 260 lb. The charge weight ratio is from 10% to 15%. Except for the 4-lb. (Butterfly bomb) all of these have cylindrical cases of uniform thickness. The 90-lb. and 260-lb. bombs are wrapped with longitudinally notched heavy coil steel springs to give improved fragmentation. Fragmentation bombs are normally used with the instantaneous nose fuzes, however the proximity fuze can be used with these bombs (except the 4-lb. bomb which also can be fuzed for long delay or anti-disturbance). The 260-lb. bomb takes a non-delay tail fuze in addition to the nose fuze. Fragmentation bombs are used against personnel, planes, motor transport, light open field placements, etc., when in the open. Due to their instantaneous fuzing fragmentation bombs are not suitable for use against targets under roofs.

d. GP (General Purpose) bombs are used in the following sizes: 100 lb., 250 lb., 500 lb., 1000 lb., and 2000 lb., (larger sizes have been introduced recently). The charge weight ratio is approximately 50%. All these bombs may be fuzed both nose and tail with the usual delays, namely, instantaneous nose, non-delay tail, 0.01, 0.025, 0.1 sec. nose and tail, short and long delay. These bombs are the most used of all types. The case is heavy enough to allow perforation of fairly resistant targets (from 1 ft. to 3 ft. of concrete, depending on the bomb size). The fragmentation and blast are effective against normally constructed targets.

e. LC (Light Case) bombs are used in the following size: 4000 lb., with a charge weight ratio of 80%. It is fuzed either instantaneous or with proximity fuze since the case will not stand impact. The fragmentation is relatively ineffective. It is used only when extensive blast is desired.

7. The British series of bombs is generally similar to the American except for different designations, and some difference in sizes and construction. Normally only tail fuzes are used, however some bombs use as many as three tail fuzes.

a. The AP bomb is 2000 lb. with a charge weight ratio of 10%.

b. The SAP bombs are 250 lb. and 500 lb. with a charge weight ratio of 18%, which is materially less than the 31% of American SAP bombs.

c. The Frag. bomb is 20 lb. with a charge weight ratio of 15%.

d. The GP bombs are 40 lb., 250 lb., 500 lb., 1000 lb., 1900 lb., and 4000 lb. The charge weight ratio is 30% (Corresponds to American SAP).

e. The MC (Medium Capacity) bombs are 500 lb., 1000 lb., 4000 lb., 12000 lb., and 22000 lb. The charge weight ratio is 40% to 50% (Corresponds to American GP)

f. The HC (High Capacity) bombs are 2000 lb., 4000 lb., 8000 lb. and 12000 lb. The charge weight ratio is 66% to 75% (Corresponds to American LC).

8. Types of Damage.

a. Contact explosion. When a bomb explodes in contact, or nearly in contact, with a target several actions combine to produce the final result. Fragments from the bomb case cut up the adjacent elements of the target. Very high compressive stresses produced in the material by the blast wave cause complete disintegration near the point of detonation, and partial disintegration at greater distances. At the same time, large stresses are produced in the comparatively undamaged regions. These are propagated as stress waves to distant parts of the target and give rise to various localized damage zones at boundaries, connections, and other points of discontinuity. The effect of detonation in contact with a concrete slab illustrates this behavior. Immediately beneath the point of detonation a hole or crater is formed. Surrounding this crater is a zone of concrete that is cracked and weakened. If the slab is of the proper thickness there will be a second crater formed on the far surface of the slab due to scabbing of concrete at the surface. The concrete between these craters may or may not be unharmed, depending on the thickness of slab. For thin slabs the craters will meet, resulting in complete perforation, while a very thick slab will normally show no effect on the far side.

b. Fragmentation. This is damage produced by missiles consisting of bomb component fragments. Only GP and Fragmentation Bombs are effective producers of fragments. The light case bombs have too few and too light fragments while the AP, and to a less extent, the SAP bombs give fragments relatively large and of low velocity making the bomb generally ineffective as a fragmentation weapon. When a bomb explodes, the case breaks up into fragments varying in size from very small to several times the case thickness The fragments are not distributed uniformly about the bomb, but tend to be concentrated in one or two zones. The most important spray (the equatorial spray) coincides approximately with the equatorial plane of the bomb. More exactly, the equatorial spray is directed about 10 degrees either ahead of, or behind the equatorial plane of the bomb, depending on whether tail or nose initiation is used. Under certain conditions this difference between nose and tail initiation becomes important, as in attacking machinery housed in one-story structures. In high order detonations fragment velocities range from about 2,000 to as much as 8,000 or more ft. per second, depending on charge weight ratio and type of explosive. Tables are available for fragmentation and GP bombs, showing /fragment patterns and velocities as well as densities of perforation achieved against various thicknesses of armor plate at different distances. (See Terminal Ballastic Data, Vol. I-Bombing, Office of Chief of Ordnance, August 1944).

Fragmentation is most effective against compact targets containing a large proportion of vital elements, for example, personnel, all types of

machinery, transportation equipment, airplanes, electrical devices, weapons. Such targets are usually fairly immune to any kind of shock, while the high proportion of vital elements makes most fragment hits effective.

The proper fragmentation weapon to use depends mostly on the vulnerability of the target, that is, on the amount of protection that must be perforated to produce an effective hit. The larger bombs have heavier fragments, consequently an increase in target resistance normally requires an increase in bomb size. For very "soft" targets, such as personnel or light, delicate mechanisms, the smallest fragmentation bombs, i.e. the 4 lb., and 20 lb., or 23 lb., are most efficient, weight for weight. For devices protected by a $\frac{1}{2}$ in. or more of steel plate such as armored guns, large transformers, armored cars, etc., 260-lb. Frag or 500-lb., and 1000-lb. GP bombs are most effective. The use of Frag bombs is limited to targets not under cover, since instantaneous or proximity fuzing is always used with them.

Fragmentation is not an effective means of damaging structures. For light single members (say roof purlins) fragmentation will sometimes cause enough damage to require replacement. Heavy beams or columns, wall panels, floors etc., may be scarred or perforated by fragments, but can be repaired quite easily unless they are so close to the point of detonation as to make it uncertain whether blast or fragmentation played the major role.

c. Debris. Structural members, floor and roof slabs, and rock particles may be effective damaging agents against fairly vulnerable targets such as personnel and delicate mechanisms. Such missiles are larger and slower than bomb fragments. Light machine tools in very long-span concrete roofed buildings have been found to suffer very considerably from debris.

d. Air, earth and water shock. Fundamentally, these are alike inasmuch as the effect is due to pressure transmitted to the target through the medium between it and the bomb. Air shock, or blast, is the most important, since most targets are above ground. A blast wave is characterized by a very steep front, corresponding to an instantaneous pressure rise, followed by a decrease to sub-atmospheric pressures, then a gradual return to normal. The peak pressure and the positive impulse (the impulse is the product of the time during which the pressure exceeds atmospheric multiplied by the average pressure during that interval) are the most important characteristics of the wave. For normal structures and the sizes of the bombs hitherto used, damage is generally considered to depend mainly on impulse. This conclusion, which is supported by experience, has permitted the extension of the very limited conclusions first drawn as to the damage areas of different weapons against different targets to various other combinations of targets and weapons. It is one purpose of this Survey to add to present knowledge and to correct the extrapolations that have been made.

For structures whose periods of vibration are short compared to the duration of the positive pressure phase it is probable that damage from external blast will depend mostly on the peak pressure of the wave. Due to the short durations of pressure pulses from the bombs used hitherto this situation has not yet been important; it may become important with extremely powerful bombs.

It has been shown that if damage depends only on impulses, then for external blast the efficiency of bombs increases with the bomb size of a

given type. On the other hand, if damage depends only on peak pressure it can be shown that the efficiency of bombs decrease with an increase in bomb size. Consequently for external blast, the situation appears to be the following:

(1) For small bombs an increase of size increases the area of destruction per unit weight of bombs;

(2) For large bombs an increase of size decreases the area of destruction per unit weight of bombs.

Therefore, if efficiency is measured in terms of damage per weight and if all bombs are used in the same way and employ the same explosive, there will be an optimum bomb size for each type of target. The above considerations apply only to the case of external or unconfined blast. In comparing the effects of explosion within the outside of a structure several additional factors become important. Confined explosions exert greater impulses than unconfined. Furthermore, structures are generally less resistant to internal than to external forces, being designed for the latter. On the other hand, an explosion inside a structure is less effective against neighboring structures than is an unconfined explosion at the same distance. So far as confined or internal explosions are concerned the optimum size of charge is one just big enough to create the required damage to the structure in which it detonates.

External blast is comparatively ineffective in small bombs; however, the efficiency increases with size. For external blast, case weight can be kept to a minimum, allowing most of the munition weight to be explosive, while cases of at least GP bomb thicknesses are needed for internal blast to insure penetration without case failure.

External blast is effective only against buildings of normal or less strength. External blast is not an efficient use of HE bombs against very resistant buildings or against gun emplacements, air raid shelters and the like. For these, internal blast is more effective, the effectiveness depending on the degree of confinement.

e. Earth Shock. Buried, or partly buried targets are frequently best attacked through ground shock. This is also true of those surface structures whose foundations are vulnerable.

An underground explosion causes ground movements and high pressures in the surrounding earth. Any structure in or on the ground in this vicinity must resist both effects. Very small structures move easily, consequently are less likely to be damaged, than are large structures. The distance at which damage can be expected is generally small, of the order of two or three crater radii from the explosion. Tests in the USA and Britain have shown the nature of the relation between damage, distance, and mount of explosive (See eg. NDRC Div 2, Weapon Data Sheet 6A5, Underground R/C Walls - Damage by Earth Shock).

f. Underwater Shock. This is generally similar to air blast and earth shock, For this reason, and because no examples of underwater shock have been examined by the Physical Damage Division, no further discussion is given here.

g. Cratering. A bomb exploding underground at not too great a depth will produce a crater. Any structure or other object extending over or into the crater may be caused to settle through removal of support. Cratering is especially effective against strongly framed buildings having shallow footings. It is also an important cause of damage to machines or equipment of considerable length or where alignment is important, as in shafting or in coupled machinery.

h. Fire from HE. In an appreciable number of cases HE bombs start fires. This occurs mainly where highly combustible materials, oils, gases, combustible dusts, etc. are present and are released by the bomb. Ignition may be caused by the hot gases of the explosion when detonation occurs very close to the ignitible material, as when a bomb explodes in an oil or gas container. Another cause of ignition is the overturning of stoves and heaters, shorting of electrical equipment and the like. In certain high temperature-high pressure processes (as in refineries, and synthetic oil and rubber plants) the hot liquids and gases are able to ignite spontaneously when released.

INCENDIARY BOMBS

9. Ways of Firing a Target. There are two ways in which incendiaries may fire a target. One is to ignite combustible material in the target. The second is to carry combustible material to the target in the bomb. As a practical matter, the second of these two methods is not very important. The size of incendiaries is necessarily limited. Even the largest ones now in use, or projected, do not produce a very big fire, that is, do not in themselves provide enough combustible material to cause a big fire.

In setting out, therefore, to damage a target, things in the target must be looked for to cause fire damage. Failure to understand this has sometimes led to erroneous conclusions as to the steps involved in bringing about destruction or damage.

10. Flight and Penetration. The steps in setting fire to a target with an incendiary begin with the dropping of the incendiary. It must have sufficient stability in flight to come down in such a manner that it will most effectively get into the target. This usually means going through the roof. The velocity must be sufficient to carry the bomb through the type of roofs and floors known to be in the target without deformation to prevent normal operation.

11. Finding Combustible Centers. Once having penetrated into the target building so as to operate as designed, the bomb must fall into or near some material to which it can set fire. Therefore, the way in which combustible material is distributed throughout a target is important. It determines the probability of the bomb striking sufficiently near to combustible material suitable to respond to its fire starting abilities. In dwelling houses and other buildings with wooden floors and roofs, there are a good many places where a bomb can come to rest on combustible material. In industrial plants, the floors and building structure may be fire-resistive or non-combustible. Hence, the bomb must find wooden partitions, piles of wooden boxes, such as "tote" boxes, wood finish or furniture. In some industries it may have to be initiated near or on piles of combustible stocks, such as rubber for example, or spilled flammable liquids.

Usually the kind of combustible material which would be ignited by an incendiary bomb is that which is of the order of kindling: paper, excelsior, thin pieces of wood, cardboard cartons, light furniture, draperies and the like. Heavy furniture, heavy woodwork and flooring are relatively more difficult to ignite. Many of the incendiaries so far developed cannot be counted upon to always ignite combustible material unless it is in the form of highly combustibles.

12. Chance of Igniting Combustibles. The next consideration is the chance that an incendiary bomb will ignite combustible material into which it falls. Of the various types of incendiary bombs some are necessarily more efficient in igniting a specific type target, than are others. It is not practicable to generalize about their relative fire-starting abilities, because it is necessary to consider how they will perform against a variety of wooden or other combustible surfaces. Because the combinations in which these surfaces may be arranged is infinite a very large number of variables is involved.

A small magnesium bomb (2-lb. or 4-lb.) will spurt light sparks of magnesium and thermite in its first minute of operation. Thereafter it settles down to steady burning for a period of about 3 minutes, during this period a person can approach within a few feet of the burning bomb. Obviously, only paper, thin wood and other readily combustible material can be ignited from such a fire.

The small oil bomb (6-lbs.) throws out a small mass of burning gel. In hitting a surface this breaks up into smaller masses, no one of which makes a big fire. It, too, can be closely approached and therefore is most likely to touch off only light combustibles.

The larger oil bombs (30-lbs., 100-lbs., 250 lb. and 500-lbs.) are more effective. They will affect a larger area because of the greater total amount of fuel in the bomb. As a rule they break up into small masses so that the fires they start must be in materials that take fire relatively easily.

The 30-lb. and larger bombs can be expected to ignite fairly heavy combustible material in some proportion of cases. But, even the largest of these bombs produces a relatively small fire at the beginning. If they are promptly attacked with even a 1/8 in. diameter hose stream discharging as little as 2 or 3 gallons of water a minute, there is a very good chance of controlling the fire.

13. Preliminary Fire Spread. a. Next in the steps in setting fire to a building is the development of the fire from the point where the bomb initiates fire. This depends on a chain of combustible material in the immediate vicinity of the point of the bomb incident.

b. In dwelling houses there is fairly continuous chains of combustible material. The floors and furniture will usually burn and also in some cases the wall finish.

c. In industrial plants, a great variety of factors determine whether a fire once started will spread. A few of these factors can be mentioned to show how complicated this particular part of the process is to appraise.

(1) Occupancy Combustiblity Scale. Storage rooms in industrial plants may be a good place to start. These usually offer a large amount of material, most of it combustible, covering a large percentage of the floor area. Even when the goods stored are non-combustible, such as metal parts, they are often packed in cardboard containers or wooden boxes. Often they are stored on wooden shelving. A particularly good example of a highly combustible occupancy is the store room for wooden patterns in a general machine shop. As a measure of occupancy combustibility of this type the pounds of combustible material per square foot would be a relatively high figure. Also there would be a continuous chain of combustible material over the entire floor area. If this is taken as the upper end, we can visualize other occupancies on a rough scale compared to it. Lower ranges in the scale involve less and less in pounds of combustible material per square foot, wider and wider spaces between groups of material, and a poorer and poorer chain of combustibles. On such a scale the next range will include certain assembly operations where a lot of small items are put together. Small items are often handled in combustible "tote" boxes or on crowded combustible benches. Still lower on the scale would be the heavier assembly operations such as those involved in air frame assembly.

When the machine shop and metal working occupancies are reached, the occupancy combustibility is quite low. Lowest of all will be such occupancies as boiler houses and power houses or rooms where the principal machines would be compressors, pumps, generators and the like.

The foregoing is by no means a complete catalogue of combustibility ratings. It may be seen, however, that they affect the extent to which a fire once started will spread.

(2) Spread Due to the Structure. In addition to occupancy causes, there are factors in the structure of the building affecting the likelihood that a fire once started will spread. In many industrial buildings, the only major combustible material may be a wooden roof which is often some height above the floor. An incendiary must come through the roof, land on the floor, and then ignite some combustible material on which to cause flames extensive enough to ignite the roof. Consequently the higher the roof the more difficult it is for it to be reached by a fire on the floor.

(3) Walls. Any wall tends to slow down a fire as the fire must find openings through which to spread. Another

type of wall is designed as a fire wall. This, by definition, is a wall which will stop the spread of fire. Usually it is construction of brick and is so thick and resistant to heat transfer that a complete burnout may occur on one side without sufficient heat being developed on the other to permit the ignition of combustible materials.

(4) Fire Divisions. A fire division, which is the area of a building within fire walls, limits the maximum size of an individual fire. Even though theoretically possible, complete burnout within a fire division does not always occur; first, because the arrangement of combustible material within the division may not be continuous; second, because there may be partitions, often of non-combustible material, which are not substantial enough to be considered as fire walls, but which will retard the spread of fire.

The foregoing discussion, for simplicity, has been principally in terms of single-story buildings. In multi-story buildings, the floors, if fire resistive, act as barriers to the spread of fire from floor to floor. Stairway openings and elevator shafts, however, are avenues for the spread of fire.

The spread of fire from building to building is principally a matter of space between the buildings, but much judgment is required to determine whether an air gap is sufficient to stop the spread of fire in a given case. Some of the factors to be taken into account are (1) combustibility of walls, (2) combustibility of occupancies, (3) size and intensity of the fire, (4) the area of exposed walls presented to one another, and (5) size of wall openings.

14. Types of Construction. The combustibility of the building structure is a factor which operates in conjunction with the occupancy and arrangement factors described. For convenience, the types of construction are grouped into four classes: combustible (C), non-combustible (N), fire resistive (R), and mixed construction.

a. Combustible construction includes those buildings which have a roof and sometimes walls of combustible material. The burning of the combustible portion can normally be expected to cause structural damage.

b. The non-combustible type has no significant amount of combustibile material, but the structure is damageable by fire in the contents Examples of this are concrete, asbestos, corrugated iron, pre-cast or poured-in-place cement or gypsum supported by exposed (bare) steel. Reinforced concrete less than 2½ in. thick is also classed in this category.

c. In fire-resistive construction, there is no significant amount of combustible material in the structure and the structure will withstand all except the most intense fire. Examples are reinforced concrete where the members are 2½ in. or more thick and where there is no unprotected steel; buildings, usually multi-story, where the steel

supporting the concrete floor and roof slabs is protected by at least 2 in. of concrete covering; the Zeiss-Dywidag construction where an arch of reinforced concrete $2\frac{1}{2}$ in. to $3\frac{1}{2}$ in. thick is used.

d. Mixed construction includes combinations of the foregoing types. A common example is a multi-story building with reinforced concrete construction except for a combustible wood roof.

15. Engineering Appraisal of Fire Vulnerability. The appraisal of the very complicated series of steps which affect the operation of incendiaries on a target would appear at first glance a somewhat hopeless task. However, it is possible to find fire protection engineers who have had experience with exactly the factors enumerated. Many of these have inspected in excess of 1000 plants and have been trained to look for the factors mentioned above. Their advice might well be sought in selecting targets for attack by incendiaries.

b. *Heavy damage*, a major part has been destroyed. Usually the machine would be returned to its manufacturer for repairs.

c. *Moderate damage*, a minor part has been destroyed which can be secured from the manufacturer or can be made and installed in the plant.

d. *Light damage*, destruction of electrical leads, or that which can be repaired by welding, etc.

Occasionally the last two of these classes are grouped together under either of the terms.

4. *Sources of Information*. In compiling this report slight use was made of reports by other organizations and of interrogations of German military and industrial personnel. Some facts were secured from the physical damage sections of plant reports written by other divisions of the Survey. The chief source of data, however, was the incident reports written by the division. These later record the findings of division personnel who accompanied industry teams on plant visits or, in many cases, the findings of teams which were organized and sent out by the division itself. A list of Physical Damage Division reports is attached hereto as Appendix A. For the convenience of those who may be interested, the reports are classified by industries in Appendix B.

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6. <u>American HE Bombs.</u>

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or 6-in. to 8-in. armor) is required. No nose fuze is used. Tail fuze is normally 0.08 sec. delay.

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d. GP (General Purpose) bombs are used in the following sizes: 100 lb., 250 lb., 500 lb., 1000 lb., and 2000 lb., (larger sizes have been introduced recently). The charge weight ratio is approximately 50%. All these bombs may be fuzed both nose and tail with the usual delays, namely, instantaneous nose, non-delay tail, 0.01, 0.025, 0.1 sec. nose and tail, short and long delay. These bombs are the most used of all types. The case is heavy enough to allow perforation of fairly resistant targets (from 1 ft. to 3 ft. of concrete, depending on the bomb size). The fragmentation and blast are effective against normally constructed targets.

e. LC (Light Case) bombs are used in the following size: 4000 lb., with a charge weight ratio of 80%. It is fuzed either instantaneous or with proximity fuze since the case will not stand impact. The fragmentation is relatively ineffective. It is used only when extensive blast is desired.

7. The British series of bombs is generally similar to the American except for different designations, and some difference in sizes and construction. Normally only tail fuzes are used, however some bombs use as many as three tail fuzes.

a. The AP bomb is 2000 lb. with a charge weight ratio of 10%.

b. The SAP bombs are 250 lb. and 500 lb. with a charge weight ratio of 18%, which is materially less than the 31% of American SAP bombs.

c. The Frag. bomb is 20 lb. with a charge weight ratio of 15%.

d. The GP bombs are 40 lb., 250 lb., 500 lb., 1000 lb., 1900 lb., and 4000 lb. The charge weight ratio is 30% (Corresponds to American SAP).

e. The MC (Medium Capacity) bombs are 500 lb., 1000 lb., 4000 lb., 12000 lb., and 22000 lb. The charge weight ratio is 40% to 50% (Corresponds to American GP)

f. The HC (High Capacity) bombs are 2000 lb., 4000 lb., 8000 lb. and 12000 lb. The charge weight ratio is 66% to 75% (Corresponds to American LC).

8. Types of Damage.

a. Contact explosion. When a bomb explodes in contact, or nearly in contact, with a target several actions combine to produce the final result. Fragments from the bomb case cut up the adjacent elements of the target. Very high compressive stresses produced in the material by the blast wave cause complete disintegration near the point of detonation, and partial disintegration at greater distances. At the same time, large stresses are produced in the comparatively undamaged regions. These are propagated as stress waves to distant parts of the target and give rise to various localized damage zones at boundaries, connections, and other points of discontinuity. The effect of detonation in contact with a concrete slab illustrates this behavior. Immediately beneath the point of detonation a hole or crater is formed. Surrounding this crater is a zone of concrete that is cracked and weakened. If the slab is of the proper thickness there will be a second crater formed on the far surface of the slab due to scabbing of concrete at the surface. The concrete between these craters may or may not be unharmed, depending on the thickness of slab. For thin slabs the craters will meet, resulting in complete perforation, while a very thick slab will normally show no effect on the far side.

b. Fragmentation. This is damage produced by missiles consisting of bomb component fragments. Only GP and Fragmentation Bombs are effective producers of fragments. The light case bombs have too few and too light fragments while the AP, and to a less extent, the SAP bombs give fragments relatively large and of low velocity making the bomb generally ineffective as a fragmentation weapon. When a bomb explodes, the case breaks up into fragments varying in size from very small to several times the case thickness The fragments are not distributed uniformly about the bomb, but tend to be concentrated in one or two zones. The most important spray (the equatorial spray) coincides approximately with the equatorial plane of the bomb. More exactly, the equatorial spray is directed about 10 degrees either ahead of, or behind the equatorial plane of the bomb, depending on whether tail or nose initiation is used. Under certain conditions this difference between nose and tail initiation becomes important, as in attacking machinery housed in one-story structures. In high order detonations fragment velocities range from about 2,000 to as much as 8,000 or more ft. per second, depending on charge weight ratio and type of explosive. Tables are available for fragmentation and GP bombs, showing fragment patterns and velocities as well as densities of perforation achieved against various thicknesses of armor plate at different distances. (See Terminal Ballastic Data, Vol. I-Bombing, Office of Chief of Ordnance, August 1944).

Fragmentation is most effective against compact targets containing a large proportion of vital elements, for example, personnel, all types of

machinery, transportation equipment, airplanes, electrical devices, weapons. Such targets are usually fairly immune to any kind of shock, while the high proportion of vital elements makes most fragment hits effective.

The proper fragmentation weapon to use depends mostly on the vulnerability of the target, that is, on the amount of protection that must be perforated to produce an effective hit. The larger bombs have heavier fragments, consequently an increase in target resistance normally requires an increase in bomb size. For very "soft" targets, such as personnel or light, delicate mechanisms, the smallest fragmentation bombs, i.e. the 4 lb., and 20 lb., or 23 lb., are most efficient, weight for weight. For devices protected by a $\frac{1}{2}$ in. or more of steel plate such as armored guns, large transformers, armored cars, etc., 260-lb. Frag or 500-lb., and 1000-lb. GP bombs are most effective. The use of Frag bombs is limited to targets not under cover, since instantaneous or proximity fuzing is always used with them.

Fragmentation is not an effective means of damaging structures. For light single members (say roof purlins) fragmentation will sometimes cause enough damage to require replacement. Heavy beams or columns, wall panels, floors etc., may be scarred or perforated by fragments, but can be repaired quite easily unless they are so close to the point of detonation as to make it uncertain whether blast or fragmentation played the major role.

c. <u>Debris.</u> Structural members, floor and roof slabs, and rock particles may be effective damaging agents against fairly vulnerable targets such as personnel and delicate mechanisms. Such missiles are larger and slower than bomb fragments. Light machine tools in very long-span concrete roofed buildings have been found to suffer very considerably from debris.

d. <u>Air, earth and water shock.</u> Fundamentally, these are alike inasmuch as the effect is due to pressure transmitted to the target through the medium between it and the bomb. Air shock, or blast, is the most important, since most targets are above ground. A blast wave is characterized by a very steep front, corresponding to an instantaneous pressure rise, followed by a decrease to sub-atmospheric pressures, then a gradual return to normal. The peak pressure and the positive impulse (the impulse is the product of the time during which the pressure exceeds atmospheric multiplied by the average pressure during that interval) are the most important characteristics of the wave. For normal structures and the sizes of the bombs hitherto used, damage is generally considered to depend mainly on impulse. This conclusion, which is supported by experience, has permitted the extension of the very limited conclusions first drawn as to the damage areas of different weapons against different targets to various other combinations of targets and weapons. It is one purpose of this Survey to add to present knowledge and to correct the extrapolations that have been made.

For structures whose periods of vibration are short compared to the duration of the positive pressure phase it is probable that damage from external blast will depend mostly on the peak pressure of the wave. Due to the short durations of pressure pulses from the bombs used hitherto this situation has not yet been important; it may become important with extremely powerful bombs.

It has been shown that if damage depends only on impulses, then for external blast the efficiency of bombs increases with the bomb size of a

given type. On the other hand, if damage depends only on peak pressure it can be shown that the efficiency of bombs decrease with an increase in bomb size. Consequently for external blast, the situation appears to be the following:

(1) For small bombs an increase of size increases the area of destruction per unit weight of bombs;

(2) For large bombs an increase of size decreases the area of destruction per unit weight of bombs.

Therefore, if efficiency is measured in terms of damage per weight and if all bombs are used in the same way and employ the same explosive, there will be an optimum bomb size for each type of target. The above considerations apply only to the case of external or unconfined blast. In comparing the effects of explosion within the outside of a structure several additional factors become important. Confined explosions exert greater impulses than unconfined. Furthermore, structures are generally less resistant to internal than to external forces, being designed for the latter. On the other hand, an explosion inside a structure is less effective against neighboring structures than is an unconfined explosion at the same distance. So far as confined or internal explosions are concerned the optimum size of charge is one just big enough to create the required damage to the structure in which it detonates.

External blast is comparatively ineffective in small bombs; however, the efficiency increases with size. For external blast, case weight can be kept to a minimum, allowing most of the munition weight to be explosive, while cases of at least GP bomb thicknesses are needed for internal blast to insure penetration without case failure.

External blast is effective only against buildings of normal or less strength. External blast is not an efficient use of HE bombs against very resistant buildings or against gun emplacements, air raid shelters and the like. For these, internal blast is more effective, the effectiveness depending on the degree of confinement.

e. Earth Shock. Buried, or partly buried targets are frequently best attacked through ground shock. This is also true of those surface structures whose foundations are vulnerable.

An underground explosion causes ground movements and high pressures in the surrounding earth. Any structure in or on the ground in this vicinity must resist both effects. Very small structures move easily, consequently are less likely to be damaged, than are large structures. The distance at which damage can be expected is generally small, of the order of two or three crater radii from the explosion. Tests in the USA and Britain have shown the nature of the relation between damage, distance, and mount of explosive (See eg. NDRC Div 2, Weapon Data Sheet 6A5, Underground R/C Walls - Damage by Earth Shock).

f. Underwater Shock. This is generally similar to air blast and earth shock. For this reason, and because no examples of underwater shock have been examined by the Physical Damage Division, no further discussion is given here.

g. Cratering. A bomb exploding underground at not too great a depth will produce a crater. Any structure or other object extending over or into the crater may be caused to settle through removal of support. Cratering is especially effective against strongly framed buildings having shallow footings. It is also an important cause of damage to machines or equipment of considerable length or where alignment is important, as in shafting or in coupled machinery.

h. Fire from HE. In an appreciable number of cases HE bombs start fires. This occurs mainly where highly combustible materials, oils, gases, combustible dusts, etc. are present and are released by the bomb. Ignition may be caused by the hot gases of the explosion when detonation occurs very close to the ignitible material, as when a bomb explodes in an oil or gas container. Another cause of ignition is the overturning of stoves and heaters, shorting of electrical equipment and the like. In certain high temperature-high pressure processes (as in refineries, and synthetic oil and rubber plants) the hot liquids and gases are able to ignite spontaneously when released.

INCENDIARY BOMBS

9. Ways of Firing a Target. There are two ways in which incendiaries may fire a target. One is to ignite combustible material in the target. The second is to carry combustible material to the target in the bomb. As a practical matter, the second of these two methods is not very important. The size of incendiaries is necessarily limited. Even the largest ones now in use, or projected, do not produce a very big fire, that is, do not in themselves provide enough combustible material to cause a big fire.

In setting out, therefore, to damage a target, things in the target must be looked for to cause fire damage. Failure to understand this has sometimes led to erroneous conclusions as to the steps involved in bringing about destruction or damage.

10. Flight and Penetration. The steps in setting fire to a target with an incendiary begin with the dropping of the incendiary. It must have sufficient stability in flight to come down in such a manner that it will most effectively get into the target. This usually means going through the roof. The velocity must be sufficient to carry the bomb through the type of roofs and floors known to be in the target without deformation to prevent normal operation.

11. Finding Combustible Centers. Once having penetrated into the target building so as to operate as designed, the bomb must fall into or near some material to which it can set fire. Therefore, the way in which combustible material is distributed throughout a target is important. It determines the probability of the bomb striking sufficiently near to combustible material suitable to respond to its fire starting abilities. In dwelling houses and other buildings with wooden floors and roofs, there are a good many places where a bomb can come to rest on combustible material. In industrial plants, the floors and building structure may be fire-resistive or non-combustible. Hence, the bomb must find wooden partitions, piles of wooden boxes, such as "tote" boxes, wood finish or furniture. In some industries it may have to be initiated near or on piles of combustible stocks, such as rubber for example, or spilled flammable liquids.

Usually the kind of combustible material which would be ignited by an incendiary bomb is that which is of the order of kindling: paper, excelsior, thin pieces of wood, cardboard cartons, light furniture, draperies and the like. Heavy furniture, heavy woodwork and flooring are relatively more difficult to ignite. Many of the incendiaries so far developed cannot be counted upon to always ignite combustible material unless it is in the form of highly combustibles.

12. Chance of Igniting Combustibles. The next consideration is the chance that an incendiary bomb will ignite combustible material into which it falls. Of the various types of incendiary bombs some are necessarily more efficient in igniting a specific type target, than are others. It is not practicable to generalize about their relative fire-starting abilities, because it is necessary to consider how they will perform against a variety of wooden or other combustible surfaces. Because the combinations in which these surfaces may be arranged is infinite a very large number of variables is involved.

A small magnesium bomb (2-lb. or 4-lb.) will spurt light sparks of magnesium and thermite in its first minute of operation. Thereafter it settles down to steady burning for a period of about 3 minutes, during this period a person can approach within a few feet of the burning bomb. Obviously, only paper, thin wood and other readily combustible material can be ignited from such a fire.

The small oil bomb (6-lbs.) throws out a small mass of burning gel. In hitting a surface this breaks up into smaller masses, no one of which makes a big fire. It, too, can be closely approached and therefore is most likely to touch off only light combustibles.

The larger oil bombs (30-lbs., 100-lbs., 250 lb. and 500-lbs.) are more effective. They will affect a larger area because of the greater total amount of fuel in the bomb. As a rule they break up into small masses so that the fires they start must be in materials that take fire relatively easily.

The 30-lb. and larger bombs can be expected to ignite fairly heavy combustible material in some proportion of cases. But, even the largest of these bombs produces a relatively small fire at the beginning. If they are promptly attacked with even a 1/8 in. diameter hose stream discharging as little as 2 or 3 gallons of water a minute, there is a very good chance of controlling the fire.

13. Preliminary Fire Spread. a. Next in the steps in setting fire to a building is the development of the fire from the point where the bomb initiates fire. This depends on a chain of combustible material in the immediate vicinity of the point of the bomb incident.

b. In dwelling houses there is fairly continuous chains of combustible material. The floors and furniture will usually burn and also in some cases the wall finish.

c. In industrial plants, a great variety of factors determine whether a fire once started will spread. A few of these factors can be mentioned to show how complicated this particular part of the process is to appraise.

(1) Occupancy Combustiblity Scale. Storage rooms in industrial plants may be a good place to start. These usually offer a large amount of material, most of it combustible, covering a large percentage of the floor area. Even when the goods stored are non-combustible, such as metal parts, they are often packed in cardboard containers or wooden boxes. Often they are stored on wooden shelving. A particularly good example of a highly combustible occupancy is the store room for wooden patterns in a general machine shop. As a measure of occupancy combustibility of this type the pounds of combustible material per square foot would be a relatively high figure. Also there would be a continuous chain of combustible material over the entire floor area. If this is taken as the upper end, we can visualize other occupancies on a rough scale compared to it. Lower ranges in the scale involve less and less in pounds of combustible material per square foot, wider and wider spaces between groups of material, and a poorer and poorer chain of combustibles. On such a scale the next range will include certain assembly operations where a lot of small items are put together. Small items are often handled in combustible "tote" boxes or on crowded combustible benches. Still lower on the scale would be the heavier assembly operations such as those involved in air frame assembly.

When the machine shop and metal working occupancies are reached, the occupancy combustibility is quite low. Lowest of all will be such occupancies as boiler houses and power houses or rooms where the principal machines would be compressors, pumps, generators and the like.

The foregoing is by no means a complete catalogue of combustibility ratings. It may be seen, however, that they affect the extent to which a fire once started will spread.

(2) Spread Due to the Structure. In addition to occupancy causes, there are factors in the structure of the building affecting the likelihood that a fire once started will spread. In many industrial buildings, the only major combustible material may be a wooden roof which is often some height above the floor. An incendiary must come through the roof, land on the floor, and then ignite some combustible material on which to cause flames extensive enough to ignite the roof. Consequently the higher the roof the more difficult it is for it to be reached by a fire on the floor.

(3) Walls. Any wall tends to slow down a fire as the fire must find openings through which to spread. Another

type of wall is designed as a fire wall. This, by definition, is a wall which will stop the spread of fire. Usually it is construction of brick and is so thick and resistant to heat transfer that a complete burnout may occur on one side without sufficient heat being developed on the other to permit the ignition of combustible materials.

(4) Fire Divisions. A fire division, which is the area of a building within fire walls, limits the maximum size of an individual fire. Even though theoretically possible, complete burnout within a fire division does not always occur; first, because the arrangement of combustible material within the division may not be continuous; second, because there may be partitions, often of non-combustible material, which are not substantial enough to be considered as fire walls, but which will retard the spread of fire.

The foregoing discussion, for simplicity, has been principally in terms of single-story buildings. In multi-story buildings, the floors, if fire resistive, act as barriers to the spread of fire from floor to floor. Stairway openings and elevator shafts, however, are avenues for the spread of fire.

The spread of fire from building to building is principally a matter of space between the buildings, but much judgment is required to determine whether an air gap is sufficient to stop the spread of fire in a given case. Some of the factors to be taken into account are (1) combustibility of walls, (2) combustibility of occupancies, (3) size and intensity of the fire, (4) the area of exposed walls presented to one another, and (5) size of wall openings.

14. Types of Construction. The combustibility of the building structure is a factor which operates in conjunction with the occupancy and arrangement factors described. For convenience, the types of construction are grouped into four classes: combustible (C), non-combustible (N), fire resistive (R), and mixed construction.

a. Combustible construction includes those buildings which have a roof and sometimes walls of combustible material. The burning of the combustible portion can normally be expected to cause structural damage.

b. The non-combustible type has no significant amount of combustibile material, but the structure is damageable by fire in the contents. Examples of this are concrete, asbestos, corrugated iron, pre-cast or poured-in-place cement or gypsum supported by exposed (bare) steel. Reinforced concrete less than 2½ in. thick is also classed in this category.

c. In fire-resistive construction, there is no significant amount of combustible material in the structure and the structure will withstand all except the most intense fire. Examples are reinforced concrete where the members are 2½ in. or more thick and where there is no unprotected steel; buildings, usually multi-story, where the steel

supporting the concrete floor and roof slabs is protected by at least 2 in. of concrete covering; the Zeiss-Dywidag construction where an arch of reinforced concrete $2\frac{1}{2}$ in. to $3\frac{1}{2}$ in. thick is used.

d. Mixed construction includes combinations of the foregoing types. A common example is a multi-story building with reinforced concrete construction except for a combustible wood roof.

15. Engineering Appraisal of Fire Vulnerability. The appraisal of the very complicated series of steps which affect the operation of incendiaries on a target would appear at first glance a somewhat hopeless task. However, it is possible to find fire protection engineers who have had experience with exactly the factors enumerated. Many of these have inspected in excess of 1000 plants and have been trained to look for the factors mentioned above. Their advice might well be sought in selecting targets for attack by incendiaries.

b. Heavy damage, a major part has been destroyed. Usually the machine would be returned to its manufacturer for repairs.

c. Moderate damage, a minor part has been destroyed which can be secured from the manufacturer or can be made and installed in the plant.

d. Light damage, destruction of electrical leads, or that which can be repaired by welding, etc.

Occasionally the last two of these classes are grouped together under either of the terms.

4. Sources of Information. In compiling this report slight use was made of reports by other organizations and of interrogations of German military and industrial personnel. Some facts were secured from the physical damage sections of plant reports written by other divisions of the Survey. The chief source of data, however, was the incident reports written by the division. These later record the findings of division personnel who accompanied industry teams on plant visits or, in many cases, the findings of teams which were organized and sent out by the division itself. A list of Physical Damage Division reports is attached hereto as Appendix A. For the convenience of those who may be interested, the reports are classified by industries in Appendix B.

5. Limitations of This Report. This report is an attempt to strike an average and draw some conclusions from the available data. Its weakness follows from the facts that: in many cases the source material is quite meagre; much of the material does not readily lend itself to summarization or averaging; and, of necessity, the work has been hurried. Concerning the first of the above facts, it is freely admitted that the material gathered, in spite of its seeming bulk, is but a small sample of what might have been secured with additional time and personnel. However, the group which has compiled the report sees no reason to suspect that consideration of a larger sample would have appreciably changed its conclusions. Concerning the second, even a slight acquaintance in the field with bomb damage, forces on the observer the conviction that there is enormous variation in results under essentially similar circumstances. Hence, two incidents at a single plant will defy a simple concise statement, and on occasions, observers at different plants will reach opposite conclusions. For this reason the serious student is advised to examine the individual incident reports of the division, which are believed, in general, to be of greater value than this present report.

HOW BOMBS PRODUCE DAMAGE

HE BOMBS

1. An HE bomb consists of a case, usually of steel, an explosive filling, and a fuze or fuzes. The function of the fuze is to detonate the filling at the proper time or place. The case serves one or more of several useful purposes. It protects the filling during storage and handling. It provides the confinement generally needed for high-order detonation of explosive. It permits the bomb to perforate or penetrate intact more or less resistant targets. Upon detonation it breaks up into fragments capable of doing damage.

2. An HE weapon causes damage in a number of different ways, namely, through contact explosion (combined damage effects); fragment; debris; air shock (blast), earth or water shock; and earth cratering due to destroying support or undermining. HE bombs also cause fires under certain conditions. As a secondary effect the deterioration of equipment from exposure to the elements is significant.

3. Different targets differ greatly in their vulnerability to each kind of action. For example, personnel, airplanes, light transport, lightly protected guns, and many types of machinery are vulnerable to fragmentation attack. Most buildings, except those of very heavy construction are vulnerable to air shock (blast), either interior or exterior. Very resistant structures above ground are most vulnerable to one of the following: contact explosion outside involving multiple causes of damage, interior air shock or blast, ground shock or cratering. Buried structures are vulnerable to contact or internal explosion or to earth shock.

4. Similarly, different weapons differ greatly in their ability to create each type of damage. A light cased bomb creates more blast, but generally produces fewer and lighter fragments than does a heavy cased bomb of the same weight. An AP (i.e. armor piercing) or SAP (i.e. semi-armor piercing) bomb has a comparatively small blast effect, due to the relatively small amount of explosive carried and to the confining action of its heavy case.

5. In selecting a weapon for a particular target it is desirable to match the maximum effectiveness of the former to the maximum vulnerability of the latter, subject to the requirement that perforation or penetration may have to be achieved without case failure, and to operational factors such as stowage and availability. In other words, targets that are vulnerable to blast are best attacked with bombs that create maximum blast.

6. American HE Bombs.

a. AP (Armor Piercing) bombs are used in the following sizes: 1000 lb. and 1600 lb. weight; the ratio of charge weight to total weight is about 15%. AP bombs are of small diameter and of stream lined shape, giving very high terminal velocity and also very high case strength. The filling is TNT or explosive D; fillings sensitive to shock are not suitable. This weapon is only used when perforation or penetration of extremely resistant targets (up to 5 ft. or 6 ft. of concrete

or 6-in. to 8-in. armor) is required. No nose fuze is used. Tail fuze is normally 0.08 sec. delay.

b. SAP (Semi-Armor piercing) bombs are used in the following sizes: 500 lb. and 1000 lb.; the charge weight ratio is about 30%. The slightly stream lined shape gives a high terminal velocity and the extra nose and case thickness insures high case strength. The filling was formerly Amatol, but later bombs are filled with TNT. These are normally used when considerable resistance to perforation has to be overcome (i.e. 3 ft. to 4 ft. of concrete or up to 3-in. armor). This bomb is normally fuzed only at the tail with the nose fuze hole closed by a steel plug.

c. Frag Bombs are used in the following sizes: 4 lb., 20 lb., 23 lb., 90 lb., and 260 lb. The charge weight ratio is from 10% to 15%. Except for the 4-lb. (Butterfly bomb) all of these have cylindrical cases of uniform thickness. The 90-lb. and 260-lb. bombs are wrapped with longitudinally notched heavy coil steel springs to give improved fragmentation. Fragmentation bombs are normally used with the instantaneous nose fuzes, however the proximity fuze can be used with these bombs (except the 4-lb. bomb which also can be fuzed for long delay or anti-disturbance). The 260-lb. bomb takes a non-delay tail fuze in addition to the nose fuze. Fragmentation bombs are used against personnel, planes, motor transport, light open field placements, etc., when in the open. Due to their instantaneous fuzing fragmentation bombs are not suitable for use against targets under roofs.

d. GP (General Purpose) bombs are used in the following sizes: 100 lb., 250 lb., 500 lb., 1000 lb., and 2000 lb., (larger sizes have been introduced recently). The charge weight ratio is approximately 50%. All these bombs may be fuzed both nose and tail with the usual delays, namely, instantaneous nose, non-delay tail, 0.01, 0.025, 0.1 sec. nose and tail, short and long delay. These bombs are the most used of all types. The case is heavy enough to allow perforation of fairly resistant targets (from 1 ft. to 3 ft. of concrete, depending on the bomb size). The fragmentation and blast are effective against normally constructed targets.

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Fragmentation is not an effective means of damaging structures. For light single members (say roof purlins) fragmentation will sometimes cause enough damage to require replacement. Heavy beams or columns, wall panels, floors etc., may be scarred or perforated by fragments, but can be repaired quite easily unless they are so close to the point of detonation as to make it uncertain whether blast or fragmentation played the major role.

c. Debris. Structural members, floor and roof slabs, and rock particles may be effective damaging agents against fairly vulnerable targets such as personnel and delicate mechanisms. Such missiles are larger and slower than bomb fragments. Light machine tools in very long-span concrete roofed buildings have been found to suffer very considerably from debris.

d. Air, earth and water shock. Fundamentally, these are alike inasmuch as the effect is due to pressure transmitted to the target through the medium between it and the bomb. Air shock, or blast, is the most important, since most targets are above ground. A blast wave is characterized by a very steep front, corresponding to an instantaneous pressure rise, followed by a decrease to sub-atmospheric pressures, then a gradual return to normal. The peak pressure and the positive impulse (the impulse is the product of the time during which the pressure exceeds atmospheric multiplied by the average pressure during that interval) are the most important characteristics of the wave. For normal structures and the sizes of the bombs hitherto used, damage is generally considered to depend mainly on impulse. This conclusion, which is supported by experience, has permitted the extension of the very limited conclusions first drawn as to the damage areas of different weapons against different targets to various other combinations of targets and weapons. It is one purpose of this Survey to add to present knowledge and to correct the extrapolations that have been made.

For structures whose periods of vibration are short compared to the duration of the positive pressure phase it is probable that damage from external blast will depend mostly on the peak pressure of the wave. Due to the short durations of pressure pulses from the bombs used hitherto this situation has not yet been important; it may become important with extremely powerful bombs.

It has been shown that if damage depends only on impulses, then for external blast the efficiency of bombs increases with the bomb size of a

given type. On the other hand, if damage depends only on peak pressure it can be shown that the efficiency of bombs decrease with an increase in bomb size. Consequently for external blast, the situation appears to be the following:

(1) For small bombs an increase of size increases the area of destruction per unit weight of bombs;

(2) For large bombs an increase of size decreases the area of destruction per unit weight of bombs.

Therefore, if efficiency is measured in terms of damage per weight and if all bombs are used in the same way and employ the same explosive, there will be an optimum bomb size for each type of target. The above considerations apply only to the case of external or unconfined blast. In comparing the effects of explosion within the outside of a structure several additional factors become important. Confined explosions exert greater impulses than unconfined. Furthermore, structures are generally less resistant to internal than to external forces, being designed for the latter. On the other hand, an explosion inside a structure is less effective against neighboring structures than is an unconfined explosion at the same distance. So far as confined or internal explosions are concerned the optimum size of charge is one just big enough to create the required damage to the structure in which it detonates.

External blast is comparatively ineffective in small bombs; however, the efficiency increases with size. For external blast, case weight can be kept to a minimum, allowing most of the munition weight to be explosive, while cases of at least GP bomb thicknesses are needed for internal blast to insure penetration without case failure.

External blast is effective only against buildings of normal or less strength. External blast is not an efficient use of HE bombs against very resistant buildings or against gun emplacements, air raid shelters and the like. For these, internal blast is more effective, the effectiveness depending on the degree of confinement.

e. Earth Shock. Buried, or partly buried targets are frequently best attacked ~~through~~ ground shock. This is also true of those surface structures whose foundations are vulnerable.

An underground explosion causes ground movements and high pressures in the surrounding earth. Any structure in or on the ground in this vicinity must resist both effects. Very small structures move easily, consequently are less likely to be damaged, than are large structures. The distance at which damage can be expected is generally small, of the order of two or three crater radii from the explosion. Tests in the USA and Britain have shown the nature of the relation between damage, distance, and mount of explosive (See eg. NDRC Div 2, Weapon Data Sheet 6A5, Underground R/C Walls - Damage by Earth Shock).

f. Underwater Shock. This is generally similar to air blast and earth shock, ~~For this reason,~~ and because no examples of underwater shock have been examined by the Physical Damage Division, no further discussion is given here.

g. Cratering. A bomb exploding underground at not too great a depth will produce a crater. Any structure or other object extending over or into the crater may be caused to settle through removal of support. Cratering is especially effective against strongly framed buildings having shallow footings. It is also an important cause of damage to machines or equipment of considerable length or where alignment is important, as in shafting or in coupled machinery.

h. Fire from HE. In an appreciable number of cases HE bombs start fires. This occurs mainly where highly combustible materials, oils, gases, combustible dusts, etc. are present and are released by the bomb. Ignition may be caused by the hot gases of the explosion when detonation occurs very close to the ignitible material, as when a bomb explodes in an oil or gas container. Another cause of ignition is the overturning of stoves and heaters, shorting of electrical equipment and the like. In certain high temperature-high pressure processes (as in refineries, and synthetic oil and rubber plants) the hot liquids and gases are able to ignite spontaneously when released.

INCENDIARY BOMBS

9. Ways of Firing a Target. There are two ways in which incendiaries may fire a target. One is to ignite combustible material in the target. The second is to carry combustible material to the target in the bomb. As a practical matter, the second of these two methods is not very important. The size of incendiaries is necessarily limited. Even the largest ones now in use, or projected, do not produce a very big fire, that is, do not in themselves provide enough combustible material to cause a big fire.

In setting out, therefore, to damage a target, things in the target must be looked for to cause fire damage. Failure to understand this has sometimes led to erroneous conclusions as to the steps involved in bringing about destruction or damage.

10. Flight and Penetration. The steps in setting fire to a target with an incendiary begin with the dropping of the incendiary. It must have sufficient stability in flight to come down in such a manner that it will most effectively get into the target. This usually means going through the roof. The velocity must be sufficient to carry the bomb through the type of roofs and floors known to be in the target without deformation to prevent normal operation.

11. Finding Combustible Centers. Once having penetrated into the target building so as to operate as designed, the bomb must fall into or near some material to which it can set fire. Therefore, the way in which combustible material is distributed throughout a target is important. It determines the probability of the bomb striking sufficiently near to combustible material suitable to respond to its fire starting abilities. In dwelling houses and other buildings with wooden floors and roofs, there are a good many places where a bomb can come to rest on combustible material. In industrial plants, the floors and building structure may be fire-resistive or non-combustible. Hence, the bomb must find wooden partitions, piles of wooden boxes, such as "tote" boxes, wood finish or furniture. In some industries it may have to be initiated near or on piles of combustible stocks, such as rubber for example, or spilled flammable liquids.

Usually the kind of combustible material which would be ignited by an incendiary bomb is that which is of the order of kindling: paper, excelsior, thin pieces of wood, cardboard cartons, light furniture, draperies and the like. Heavy furniture, heavy woodwork and flooring are relatively more difficult to ignite. Many of the incendiaries so far developed cannot be counted upon to always ignite combustible material unless it is in the form of highly combustibles.

12. Chance of Igniting Combustibles. The next consideration is the chance that an incendiary bomb will ignite combustible material into which it falls. Of the various types of incendiary bombs some are necessarily more efficient in igniting a specific type target, than are others. It is not practicable to generalize about their relative fire-starting abilities, because it is necessary to consider how they will perform against a variety of wooden or other combustible surfaces. Because the combinations in which these surfaces may be arranged is infinite a very large number of variables is involved.

A small magnesium bomb (2-lb. or 4-lb.) will spurt light sparks of magnesium and thermite in its first minute of operation. Thereafter it settles down to steady burning for a period of about 3 minutes, during this period a person can approach within a few feet of the burning bomb. Obviously, only paper, thin wood and other readily combustible material can be ignited from such a fire.

The small oil bomb (6-lbs.) throws out a small mass of burning gel. In hitting a surface this breaks up into smaller masses, no one of which makes a big fire. It, too, can be closely approached and therefore is most likely to touch off only light combustibles.

The larger oil bombs (30-lbs., 100-lbs., 250 lb., and 500-lbs.) are more effective. They will affect a larger area because of the greater total amount of fuel in the bomb. As a rule they break up into small masses so that the fires they start must be in materials that take fire relatively easily.

The 30-lb. and larger bombs can be expected to ignite fairly heavy combustible material in some proportion of cases. But, even the largest of these bombs produces a relatively small fire at the beginning. If they are promptly attacked with even a 1/8 in. diameter hose stream discharging as little as 2 or 3 gallons of water a minute, there is a very good chance of controlling the fire.

13. Preliminary Fire Spread. a. Next in the steps in setting fire to a building is the development of the fire from the point where the bomb initiates fire. This depends on a chain of combustible material in the immediate vicinity of the point of the bomb incident.

b. In dwelling houses there is fairly continuous chains of combustible material. The floors and furniture will usually burn and also in some cases the wall finish.

c. In industrial plants, a great variety of factors determine whether a fire once started will spread. A few of these factors can be mentioned to show how complicated this particular part of the process is to appraise.

(1) Occupancy Combustiblity Scale. Storage rooms in industrial plants may be a good place to start. These usually offer a large amount of material, most of it combustible, covering a large percentage of the floor area. Even when the goods stored are non-combustible, such as metal parts, they are often packed in cardboard containers or wooden boxes. Often they are stored on wooden shelving. A particularly good example of a highly combustible occupancy is the store room for wooden patterns in a general machine shop. As a measure of occupancy combustibility of this type the pounds of combustible material per square foot would be a relatively high figure. Also there would be a continuous chain of combustible material over the entire floor area. If this is taken as the upper end, we can visualize other occupancies on a rough scale compared to it. Lower ranges in the scale involve less and less in pounds of combustible material per square foot, wider and wider spaces between groups of material, and a poorer and poorer chain of combustibles. On such a scale the next range will include certain assembly operations where a lot of small items are put together. Small items are often handled in combustible "tote" boxes or on crowded combustible benches. Still lower on the scale would be the heavier assembly operations such as those involved in air frame assembly.

When the machine shop and metal working occupancies are reached, the occupancy combustibility is quite low. Lowest of all will be such occupancies as boiler houses and power houses or rooms where the principal machines would be compressors, pumps, generators and the like.

The foregoing is by no means a complete catalogue of combustibility ratings. It may be seen, however, that they affect the extent to which a fire once started will spread.

(2) Spread Due to the Structure. In addition to occupancy causes, there are factors in the structure of the building affecting the likelihood that a fire once started will spread. In many industrial buildings, the only major combustible material may be a wooden roof which is often some height above the floor. An incendiary must come through the roof, land on the floor, and then ignite some combustible material on which to cause flames extensive enough to ignite the roof. Consequently the higher the roof the more difficult it is for it to be reached by a fire on the floor.

(3) Walls. Any wall tends to slow down a fire as the fire must find openings through which to spread. Another

type of wall is designed as a fire wall. This, by definition, is a wall which will stop the spread of fire. Usually it is construction of brick and is so thick and resistant to heat transfer that a complete burnout may occur on one side without sufficient heat being developed on the other to permit the ignition of combustible materials.

(4) Fire Divisions. A fire division, which is the area of a building within fire walls, limits the maximum size of an individual fire. Even though theoretically possible, complete burnout within a fire division does not always occur; first, because the arrangement of combustible material within the division may not be continuous; second, because there may be partitions, often of non-combustible material, which are not substantial enough to be considered as fire walls, but which will retard the spread of fire.

The foregoing discussion, for simplicity, has been principally in terms of single-story buildings. In multi-story buildings, the floors, if fire resistive, act as barriers to the spread of fire from floor to floor. Stairway openings and elevator shafts, however, are avenues for the spread of fire.

The spread of fire from building to building is principally a matter of space between the buildings, but much judgment is required to determine whether an air gap is sufficient to stop the spread of fire in a given case. Some of the factors to be taken into account are (1) combustibility of walls, (2) combustibility of occupancies, (3) size and intensity of the fire, (4) the area of exposed walls presented to one another, and (5) size of wall openings.

14. Types of Construction. The combustibility of the building structure is a factor which operates in conjunction with the occupancy and arrangement factors described. For convenience, the types of construction are grouped into four classes: combustible (C), non-combustible (N), fire resistive (R), and mixed construction.

a. Combustible construction includes those buildings which have a roof and sometimes walls of combustible material. The burning of the combustible portion can normally be expected to cause structural damage.

b. The non-combustible type has no significant amount of combustibile material, but the structure is damageable by fire in the contents. Examples of this are concrete, asbestos, corrugated iron, pre-cast or poured-in-place cement or gypsum supported by exposed (bare) steel. Reinforced concrete less than 2½ in. thick is also classed in this category.

c. In fire-resistive construction, there is no significant amount of combustible material in the structure and the structure will withstand all except the most intense fire. Examples are reinforced concrete where the members are 2½ in. or more thick and where there is no unprotected steel; buildings, usually multi-story, where the steel

supporting the concrete floor and roof slabs is protected by at least 2 in. of concrete covering; the Zeiss-Dywidag construction where an arch of reinforced concrete $2\frac{1}{2}$ in. to $3\frac{1}{2}$ in. thick is used.

d. Mixed construction includes combinations of the foregoing types. A common example is a multi-story building with reinforced concrete construction except for a combustible wood roof.

15. Engineering Appraisal of Fire Vulnerability. The appraisal of the very complicated series of steps which affect the operation of incendiaries on a target would appear at first glance a somewhat hopeless task. However, it is possible to find fire protection engineers who have had experience with exactly the factors enumerated. Many of these have inspected in excess of 1000 plants and have been trained to look for the factors mentioned above. Their advice might well be sought in selecting targets for attack by incendiaries.

HIGH EXPLOSIVE BOMB DAMAGE TO BUILDINGS AND INSTALLATIONS

1. General. This part of the report deals with HE weapons and their damaging effects upon structures and installations under the following headings:

a. Industrial type buildings.

b. Heavy structures (gun emplacements, submarine pens, fortifications, coking plants).

c. Bridges.

d. Chimneys (masonry type).

e. City areas.

2. HE bomb damage only, has been considered in the text and tabulations except in the section which covers City areas. In this part of the report, HE bomb damage includes any fire damage which was caused by the detonation of HE weapons but does not include any "Mixed" damage which could have been caused by the joint action of HE and IB weapons.

3. The material analyzed has been extracted from Physical Damage Division reports covering the results of field surveys of the various targets. Table 4 lists the Physical Damage Division reports by number and title from which the pertinent data for industrial type buildings has been taken. The report numbers and titles covering source data for other installations have been referred to in the text.

4. The attempt has been made in the report to associate the HE bomb damage effects upon buildings with the structural vulnerability classification of the structure and the weapon used. In certain of the vulnerability classifications sufficient data for an effective study are lacking and that limitation must be recognized. It will be noted that the foregoing applies only to U.S. and British bombs, principally of the 500-lb. and 1000-lb. sizes. A large bomb detonation (4000-lb. and above) invariably affects buildings of more than one structural type, due to its large near-miss radius, whereas the smaller bomb has a smaller near-miss range in causing structural damage. The smaller size bomb effects are therefore more likely to be confined to the structure directly adjacent to their points of impact. This is not true of the larger sizes of bombs and the measure of their effectiveness should be obtained from the section of the report dealing with mean areas of effectiveness of HE weapons.

HE Weapons Used.

5. The following HE weapons were used to inflict damage on industrial targets which are listed in Table 4:

7. HE Bomb Damage to Industrial Buildings. Table 4 contains a compilation of data for all damaged buildings included in the targets as listed in the Table. The buildings damaged were principally of the factory type and the various appurtenant buildings usually found in industrial plants; the structures were predominantly single-story but a number of multi-story buildings were also damaged.

Table 4 lists twenty-two (22) different targets and a summary of the HE bomb damage suffered by these objectives is given below:

No. of Targets.	Plan Area of the Damaged Bldgs. Acres.	Total Floor Area of Damaged Bldgs. Acres.	Total Area of Struct'l Roof Damage Acres	Total Area of Struct'l Floor Damage Acres.
22	217	253	83	15

Total Area of Supf'l Damage Acres	Fraction of Struct'l Roof Damage	Damaging HE Bombs Tons	Struct'l Damage (Roof plus Floor) in Acres/Ton
47.5	.38	420.3	0.23

One Ton = 2000 lbs.

Fire damage to roof structures, caused by HE bombs, was insignificant in amount but this category of damage accounted for 20.4% of the total area of floor damage listed. The difference in the amount of HE-fire damage suffered by roofs and floors was probably due to the ignition and burning of contents on the floors caused by detonation of the bombs.

8. Damage to Structural Types of Buildings caused by U.S. and British 500-lb. and 1000-lb. HE Bombs. Damage and bomb data has been lifted from the reports, listed in Table 4, referring to U.S. and British 500-lb. and 1000-lb. HE bombs, but only those items of damage which were definitely tied back to a specific weapon and to a specific structural type were extracted to avoid confusion with the effects of other weapons. Buildings of different construction have different vulnerabilities to HE bombing, in general, and a division of buildings into structural types has been made in order to compare the damage to the respective types caused by a given weapon. The structural types are indicated below:

Symbol	Description
	Single-Story Buildings
1/a	Masonry load bearing wall types
1/b	Light factory types; steel or wood framed
1/c	Heavy steel framed or those containing runways that support heavy cranes.

Symbol	Description
1/d	Hangar and Aircraft assembly types; steel, timber or reinforced concrete framed roofs
1/c	Factory reinforced concrete framed or shell types
1/f	Miscellaneous buildings of light construction.
	Multi-Story Buildings
M/a	Masonry load bearing wall types or those of composite construction
M/b	Steel framed
M/c	Reinforced concrete framed or flat slab construction.

The above structural types have been used in Table 1-3, which compare the damage effects of U.S. and British, 500-lb. and 1000-lb. bombs.

9. Table 1 separates U.S. and British bombs of the 500-lb. and 1000-lb. sizes by the fuzings used; structural roof damage, the number of bombs inflicting the damage and the structural roof damage in acres/ton is indicated for the purposes of comparison. Due attention must be given to the number of cases involved; the reliability of the values in column 10 is contingent upon the number of buildings attacked with the weapon.

a. Few cases were available for the British bombs of the 500-lb. and 1000-lb. sizes and the data for the 1/c, 1/c and 1/f structural types for the 1000-lb. MC appears to be the best.

b. U.S. 500-lb. GP - The most reliable data is shown for the 1/a, 1/b and the 1/f structural types. The 0.01 sec. tail delay fuze produced more damage per ton of HE than the 0.025 sec. tail delay fuze, except for type 1/f where the result was nearly equal. Data for the multi-story type in Table 3, are inadequate in amount for conclusions.

c. U.S. 1000-lb. GP - This weapon does not appear to be as efficient for causing damage as the 500-lb. GP, but additional incidents are required for a true evaluation. The 0.025 sec. tail fuze fitted to this weapon appears to produce more damage than the 0.01 sec. tail fuze.

d. British 500-lb. MC - Insufficient data does not permit any appraisal of this weapon to cause damage.

e. British 1000-lb. MC - the best data for this weapon is shown against the 1/c structural type where the 0.01 sec. delay fuze

seems more efficient in producing damage. Against the 1/f structural type the 0.025 delay fuze was better than non-delay but an insufficient number of cases will not support a conclusion. The 1000-lb. MC fuzed 0.025 sec. delay shows better results against the 1/c structural type than the U.S. 1000-lb. GP. fuzed 0.025 sec. tail delay.

10. Table 2 has been prepared to indicate the effect of U.S. 500-lb. and 1000-lb. GP bombs against the structural types, regardless of fuzings. Incidents have been added to those shown in Table 1 to include those buildings which were attacked with bombs fitted with mixed fuzings. Sufficient data for accurate study are not available for the following items:

HE Weapon	Structural Type
U.S. 500-lb. GP	1/c
Br. 1000-lb. MC	1/a, 1/f.

Table 2 suggests that the U.S. 500-lb. GP is a more efficient weapon against the various structural types than the U.S. 1000-lb. GP. The British 1000-lb. MC type shows superiority over the U.S. 1000-lb. GP in attacking structures of type 1/c, but is inferior against type 1/e structures, on the basis of the data listed.

HEAVY STRUCTURES.

11. Submarine Pens. Reports 10 and 39 cover the results of bombing attacks on the submarine pens located at Brest, France, and Hamburg, Germany respectively. In both instances 12000-lb. (Tallboy) bombs, employing various fuze settings, were the weapons used in the attacks. Results of the surveys show that little effective damage was accomplished and in neither case were the pens rendered unserviceable. A description of each target and summary of damage inflicted follows:

12. Submarine Pens at Brest, France (PDD 10). This structure was constructed of reinforced concrete of excellent design and strength. It was 1200 feet long by 600 feet wide and contained 15 submarine pens. Original construction had a flat reinforced concrete roof varying in thickness from 12 ft. 8 in. to 14 ft. However the protective quality of the roof was supplemented by several methods on different roof areas. In some areas an additional 5 ft. of reinforced concrete was poured directly on the original roof without bonding by reinforcement steel. On other areas precast concrete blocks were laid, and on others a slightly pitched roof of reinforced concrete was erected. In the latter areas an air space existed between the original roof and supplementary protection. This pen received nine direct hits by 12000-lb. (Tallboy) British bombs. Five were fuzed for 11 sec. delay action and four were fuzed 0.5 sec. delay. In addition two of the same type bombs fuzed 0.5 sec. detonated near the rear side of the pen. In all direct hits the bombs failed to penetrate the roof prior to detonation. Strikes on roof spans either resulted in craters with accompanying under-roof spalling or hour-glass shaped openings. Strikes on areas directly over heavy partition walls resulted in roof craters and spalling on the underside of the roof and partition wall. In no case did serious structural damage occur such as roof collapse or wall cracking. Minor damage occurred to interior facilities such as crane rails, air and electric lines, walkways and hand rails by falling debris from the roof spalls. The two strikes at the rear of the structure caused no damage to the main building but demolished a few nearby buildings of light construction.

13. Submarine Pens at Hamburg, Germany (PDD 39) This structure was constructed of reinforced concrete of excellent design and strength. It was 518 ft. long by 442 ft. wide and had a flat reinforced concrete roof varying in thickness from 10 ft. to 11 ft. 6 in. This pen received six direct hits by 12000-lb. (Tallboy) British bombs all fuzed 25 to 30 sec. delay. In addition one near miss by the same type bomb and same fuzing occurred 100-ft. from the west sidewall of the structure. As in the cases of the strikes on the pens at Brest, France, none of the direct hits penetrated the roof prior to detonation. Crater data and interrogation of witnesses resulted in the conclusion that all bombs detonated non-delay after penetrating about 3 ft. into the roof concrete. Strikes on the roof resulted in each case, of hour-glass shaped openings ranging in lip diameter from 14 to 25 ft. and in throat diameter from 9 to 16 ft. with the minimum section occurring from 3 to 5 ft. below the roof surface. No major structural damage, such as roof collapse or fracturing, resulted from the hits. Minor damage to operating devices inside the pens resulted

from falling debris. The near miss caused settlement and lateral displacement of the west wall but did not materially effect the stability of the structure nor prevent its continued use as a submarine pen.

14. Coking Plants. Physical Damage Report 13 covered the survey of bomb damage to coking plants, located at Montigny and Liege, Belgium. In addition the Munitions Division of the Survey issued report "The Coking Industry in Germany". The interested reader will find details in these two reports.

15. Gun Emplacements. Physical Damage Division Report 1 covers the results of bombing attacks on four 15-cm gun emplacements located near Longues, France. The target consisted of an area which included not only the four separate gun emplacements but also communication tunnels and trenches, personnel shelters, ammunition storage shelters and observation posts. The area was well saturated with bomb hits which included two direct hits on structures and two near-miss hits to structures. Positive identification of the size and fuzing of the bombs was not possible but in the opinion of the survey party all strikes were made by 1,000-lb. GP bombs fuzed with 0.1 sec. nose and 0.01 sec. tail fuzes. Damage resulting from these four hits is described in the following:

a. One direct hit and two near misses occurred at Gun Emplacement 2. The direct hit struck on the roof of the left wing which, at the point of contact, was estimated to be four to five feet in thickness and was constructed of reinforced concrete. This bomb penetrated the roof and resulting blast destroyed the westwall and fractured the east interior wing wall from the ceiling to the floor. One near miss, striking three feet from the front corner of Emplacement 2, badly cracked the concrete gun base probably putting the gun out of action. Another near miss two feet from the right wing of the emplacement apparently caused no material structural damage.

b. One direct hit occurred on the roof of an ammunition storage shelter. This building was constructed of reinforced concrete having a 3-foot reinforced concrete roof. The bomb penetrated the roof and completely demolished the shelter.

16. Fortifications. Physical Damage Report 14 covers the survey of bomb damage to Fort Saint Blaise at Metz, France. At different times this tactical target was attacked by ground troops using artillery up to 250 mm; by fighter bombers dropping 250- to 1000-lb. bombs (no structural damage was apparent from these attacks by the ground forces and the fighter bombers); and, on 8 October 1944 by B-26's, dropping 2000-lb. bombs. Of these 2000-lb. bombs, six were direct hits and four were near-misses. The analysis in PDD 14 treats with damage caused by the 2000-lb. bombs and may be seen for details.

BRIDGES

17. Physical Damage Division Reports 26 and 27 cover the bomb damage to one combination highway and railway bridge and to one railway bridge. A description of each target and damage inflicted thereon follows:

18. Combination Highway and Railway Bridge. Report 26 deals with attacks on a bridge over the Noho River at Bad Munster, Germany. The bridge was 370-ft. long by 59 ft. wide and consisted of three separate structures resting on the same piers and abutments. The longitudinal axis of the bridges was approximately north-south. A steel truss type highway bridge was located on the west side, a steel truss railway bridge was located on the east side and a plate-girder type railway bridge was located between the two previously mentioned structures. Each bridge was constructed in four 92 ft. spans resting on stone masonry abutments and piers. On 26 December 1944 this bridge was attacked by medium bombers of the Ninth Air Force and received three direct hits on the superstructure, one direct hit and one near miss on the south abutment. All bombs inflicting damage consisted of 1000-lb. GP's, fuzed 0.1 sec. nose and 0.01 sec. tail. Damage to the bridge caused by each bomb hit is described in the following table:

DAMAGE DATA

Combination Highway and Railway Bridge

Bomb No.	Location of Hit.	Depth of Penetration	Description of Damage
1.	On highway, near inside truss 70' from first pier from south end of bridge.	4' below road level.	Shattered roadway decking. Minor damage to structural framing. Superficial damage to nearby pier and adjacent plate girder.
2.	Center of highway immediately over first pier from south end of bridge.	Penetrated pin $3\frac{1}{2}$'	Destroyed a large portion of the pier. Displaced both spans of highway bridge from their bearings. Damaged the bearing of the adjacent plate girder railway span to such an extent it required replacing for serviceability.
3.	Center of railroad bed. Truss structure. 65' from south abutment.	Penetrated 8' into soil of river bank.	Exact damage to structure inflicted by this bomb not determinable because span had been removed by demolition preparatory to reconstruction.

Bomb No.	Location of Hit.	Depth of Penetration	Description of Damage
4.	In fill just to rear of southeast end of south abutment.	Penetrated 9-ft. in to fill.	Demolished a section of abutment under bearing of railroad span causing the end of the span to fall to the ground.
5.	Near miss 10' northwest of the end of south abutment.	Penetrated 9' into earth.	No damage to abutment. Probably helped in the displacing of roadway bridge span from bearing but evidence is not conclusive to this effect.

19. Railway Bridge. Report 27 deals with a double track railway bridge over the Moselle River at Eller, Germany. The bridge was a deck-type, steel-truss, 925 ft. long by 30 ft. wide, resting on stone masonry piers and abutments. The longitudinal axis of the bridge extended in north-south direction. The bridge consisted of six spans, three of which located on the south side of the river had been destroyed by demolition and were inaccessible to the survey party. Span length of the remaining three, measuring from the north abutment, were 123 ft., 136 ft. and 123 ft. in that order. Three direct hits by 1000-lb. GP bombs, fuzed 0.1 sec. nose and non-delay tail, occurred on the three spans under study. At the time of inspection repair work had been completed to the extent that the west track had been placed in serviceable condition and the east track had been partially repaired. A description of the damage inflicted by each bomb is included in the following Table:

DAMAGE DATA

Railway Bridge

Bomb No.	Location of Hit.	Depth of Penetration.	Description of Damage.
1.	End span 29' from north abutment. Center line of east track.	2 ft. below the top of wood cross-ties.	All damage was repaired requiring replacement of 60 ft. of rails and ties. Replacement of 25 ft. of each 16" in. I-beam. Replacement of 25 ft. of each top truss chord. Chord Section Top flange - 20 in. by $\frac{3}{4}$ in. plate Web - 16 in. by $\frac{3}{8}$ in. plate Angles - 4 in. by 4 in. by $\frac{1}{2}$ in. Additional minor damage to sway bracing and hand rails.