THE PHYSICS OF AIR RAIDS*

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A GREAT deal of the terrifying effect of bombs has been due to our lack of knowledge of the processes that take place. It is naturally difficult to study events which take place with the rapidity and violence of explosions, but it is not impossible, and thanks to the work of a large number of physicists in many countries before the War, and particularly in Great Britain during the War in the laboratories of the Department of Scientific and Industrial Research, we may say that the main features of the physical processes involved in explosions are becoming well understood. Naturally it is impossible to give here more than the broadest outlines of our present knowledge, both on account of its intricate nature and even more because of the requirements of secrecy.

Most of the effects of explosives on materials can be best understood by considering the explosive to generate a wave of extremely high intensity travelling through the body at a very high speed. Normally, mechanical disturbances travel in materials at the speed of sound, a speed which is determined by the square root of the ratio of the density of the body to its elasticity. Where the density is large and the elasticity small, waves travel slowly, and vice versa, the limits being between about 500 ft. a second in carbon tetrachloride vapour to 17,000 ft. a second in steel. For the high pressures which exist near explosions, much greater velocities occur. This is because the elasticity of bodies depends on the pressure; the interiors of atoms are more rigid than their outer surfaces. On intense compression a high elasticity and therefore a more rapid wave is produced. This is, of course, much more marked in gases than in solids and liquids. The velocity of sound in water may change from 6,000 to 12,000 ft. a second in the neighbourhood of an explosion, but that in air will change from 1,000 to about 20,000 ft. a second.

There is also a change in the character of the wave. High-pressure waves have not the smooth wave form of ordinary sound waves. Instead, the pressure in front of the wave rises immediately to its highest value and then falls off gradually and is followed by a phase of less than atmospheric pressure or suction (Fig. 1). The generation of this steep-fronted or shock wave is very similar to that of the waves which break on the sea-shore; the high-pressure phase of the disturbance, always travelling faster than the low-pressure phase, gets to the front, just as the top of the wave on the sea-shore, being held back less than the base by the friction of the sand, moves forward and ultimately breaks the wave. The shock wave is always breaking, as the free front portion is losing energy more rapidly than that behind and consequently, quite apart from the spreading of the wave, it is always dying down, most quickly, of course, nearest the explosion, and ultimately it degenerates into an ordinary sound wave.

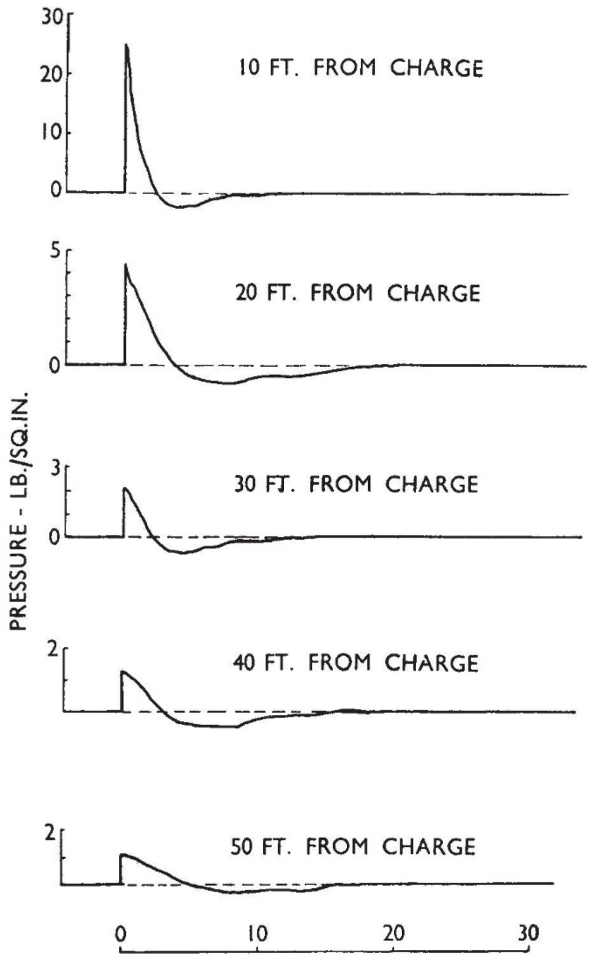

Fig. 1.

PRESSURE-TIME CURVES OF BLAST FROM 2-LB. CHARGE OF BLASTING POWDER.

* From a special afternoon lecture delivered at the Royal Institution on December 3.

The shock wave in air is what is usually known as blast and is responsible for most of the slighter effects of air raids, such as breaking of windows. The pressures needed to do this are not very considerable. Pressure peak values of 1–10 lb. per square inch, or less than an extra atmosphere, are able to break most windows, but peak pressures have to rise to about 100 lb. per square inch, or 6 atmospheres, before human beings are endangered, and this only occurs very close to explosions, so that in fact very few people are directly injured by blast. The shock wave, however, is not only an increase in pressure. Immediately behind the wave front the air is moving forward and there is an initial forward push followed by a backward pull. This, of course, can move loose objects about and throw people down or throw other things on top of them. Most injuries due to blast are only secondary in this sense and usually not very serious.

The freakish effects of blast on windows are not only due to the great variety of windows used. The shock wave behaves like any other wave in that it is reflected with more or less absorption from everything that it strikes. In streets, particularly with tall houses, this reflexion is almost complete. Consequently, a bomb exploding in a street sets up a series of reflected waves which at a considerable distance are like a periodic disturbance. If it happens that a window has a similar natural frequency, this periodic disturbance may break it by resonance. Consequently, isolated windows are often found broken at great distances from bombs.

Another so-called freak effect is due to the fact that a shock wave in a narrow street is reflected in a different way from the opening at the top of the street. A compression wave travelling in an open-ended pipe produces, when it reaches the end, a reflected suction wave, as the air having been driven out of the pipe a temporary vacuum is left behind. When this happens in a street, the reflected suction wave may be much stronger than the original suction wave of the bomb and may produce violent effects on windows and doors in lower stories, drawing them out towards the street.

A shock wave behaves in a characteristic way towards limited obstacles. Ordinary sound waves throw shadows only from the largest obstacles, such as hills or high buildings, because their wave-length is of the order of 10–100 ft. A shock wave, strictly speaking, has no single wave-length but a number of wave-lengths. The sharp high-pressure part has a very small wave-length and the tail suction part has a very long one. Consequently a shock wave passing through an aperture or round an obstacle is changed in character. Roughly speaking, the pressure part goes straight and casts shadows, whereas the suction part travels round corners without any difficulty. Thus behind a wall the pressure part of the wave may be cut down to about a tenth without making any difference to the suction part. This is very useful, as it has been shown that it is the pressure part of the wave that is responsible for most physiological damage. To have even a small garden wall between oneself and the bomb is practically to be secure from direct effects of blast. On the other hand, an open doorway is a danger and the necessity of putting baffles in front of Anderson shelter entrances applies to the blast as much as it does to the splinters.

Much of the terror attached to bombs has been due to stories of people being killed at great distances, without any physical injuries, by the mysterious effect of blast. Investigation has shown that the effect of the blast wave is that of a simple blow on the body. Most of the body is solid; the only empty parts are the lungs, and

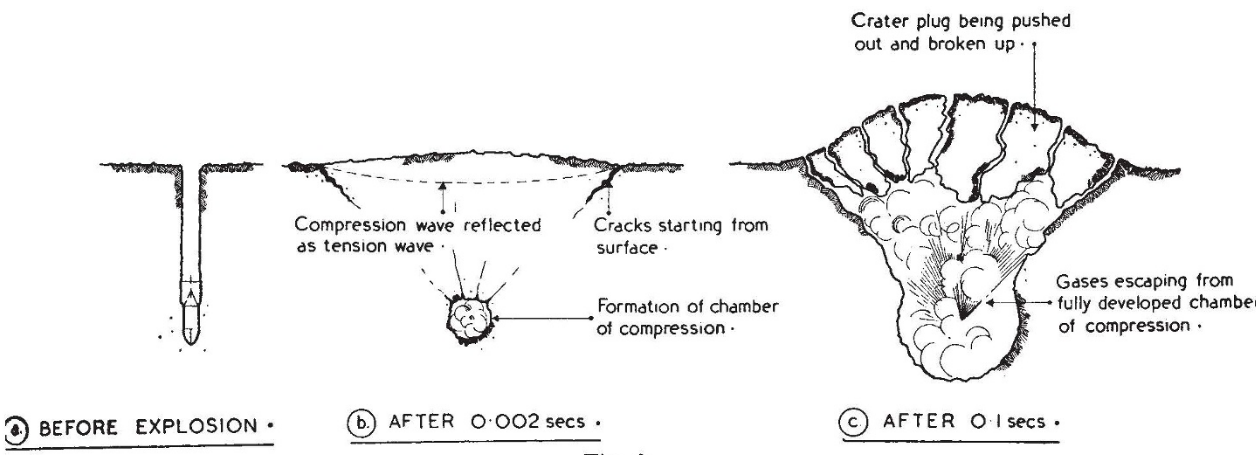

Fig. 2.

the effect of blast is essentially to bruise the lungs through the chest wall. This is effected only by the pressure part of the wave; the suction has no effect. Fortunately lungs will stand a great deal of bruising without permanent injury, and though quite a number of blast cases have occurred, most of them have recovered. Now that the nature of the injury is known, they can be treated as non-infected pneumonias, which, in practice, means only rest in bed.

Apart from blast, the main damage produced by bombs is due to splinters and earth shock. When a bomb bursts, the case first swells and then breaks up in a way very similar to the bursting of a gas cylinder under excess pressure. Failure takes place in tension along planes at 45° to the bomb surface, yielding angular fragments which are driven forward by the expanding gases. They therefore have very high velocities up to about 4,000 ft. a second and consequently have very considerable penetration into materials. The fragments are of all sizes, ranging from lumps of 40 lb. or more down to the most minute dust. As a result of experiments largely carried out since the War began, we are beginning to understand the mechanism of penetration of these fragments and the best ways of stopping them. Luckily the cheapest materials are, in fact, very effective. Three feet of sandbags have stopped any small fragment that has occurred in this War, and 13½ in. of brick will stop all but the biggest.

Only a proportion of bombs actually explode on the surface, usually on streets or concrete slabs; the great majority penetrate either into buildings or into the ground. The characteristic crater is that produced by a bomb exploding about 10–20 ft., according to size, underground. The damage done by such bombs is not due either to blast or splinters, but to the effect of the explosion on the earth. When a bomb explodes in a dense medium, such as soil, it produces a shock wave travelling at velocities which depend on the nature of the soil. As all soils get more elastic as they go deeper, the shock wave travels in a complicated way; it is reflected from the lower levels, and at distances of more than 100 ft. has already become a complex train of waves very similar to those found in earthquakes. Such waves can shake down buildings in a somewhat capricious way, depending on the natural frequencies of the building in relation to that of the waves, but generally speaking only old or badly built buildings are affected.

The most serious effects of ground shock are those nearer to the explosion, and are not due to the shock wave but to the bodily movement of the earth near the bomb. After explosion the explosive gases push the earth aside, forming an initial sphere of expansion. The displaced earth is moved outwards and quite considerable displacements occur. The displacement is partly elastic and partly plastic. The earth may be moved some inches and come back to within half an inch of where it started. This earth movement is, of course, mostly dangerous to underground structures. It is not so much an instantaneous blow as a steady pressure exerted for a time of the order of 0·1 sec. It is least effective on structures which can yield to such pressures without breaking. One of the main advantages of the Anderson shelter is its flexible character. This earth movement is usually responsible for the breaking of gas and water mains by bombs.

When the shock wave from an underground bomb reaches the surface, it is reflected as a tension wave, and if it is strong enough the ground cracks and a conical 'scab' is formed which is projected upwards, usually breaking up and leaving the characteristic crater behind. The observed crater, of course, is always complicated by the presence of material which has been thrown out and fallen back into it. The true crater is usually almost twice as deep. If the bomb is too deep, the breaking of the surface does not occur; it is simply heaved up and drops back more or less into place. This is called a 'camouflet'. Such camouflets are usually of little importance, except that they may be mistaken for unexploded bombs.

When a bomb strikes a building the effects are naturally complex, but they depend on relatively few principles. When a bomb explodes in a house its primary effect is to cause a blast wave which, meeting walls, blows them out. The effect is greater than blast in the open because the waves reflected from other walls add their effect to that of the initial blast, producing a more prolonged pressure and consequently a greater outward momentum. Except in very large halls or sheds, this blast pressure is sufficient to break the wall and project a considerable portion of it clear of the building. What happens afterwards depends on the type of the building. In favourable cases the only result is to form a hole in one or more external walls, the remaining part of the building holding together. More often the damage to the walls causes partial or complete collapse of the building. With steel-framed or reinforced concrete buildings the frame prevents the falling of the upper part of the building and holds up the comparatively small load produced by the immediate effects of the explosion.

This outline of some physical aspects of air-raid damage shows that we have a quantitative picture of the dangers of raids; this is the first step in providing rational means of minimizing them.