The Behaviour of Time Fuzes.

By PROF. A. V. HILL, F.R.S.

THE time fuze is a device for exploding a shell at any desired interval after it is fired. Before the late war the time fuze was used mainly with shrapnel shell, to burst the shell in the air and so propel the bullets down on to the objective. For this purpose the ordinary "powder-train" fuze gave—considering its simplicity—remarkably good and consistent results; at any rate so good that no serious impetus had been given to a proper scientific study of its properties under a variety of conditions. The development of anti-aircraft gunnery, however, in which the employment of a percussion fuze was useless, and in which the target moved so fast that no preliminary "ranging" on it was possible, not only required a much greater reliance to be placed on the accuracy of the time fuze, but also subjected it to much more severe conditions than had ever occurred before. The conditions referred to were those set up by variations of velocity, air pressure, spin, and temperature. Moreover, the enormous quantity of powder suddenly required for military use made it difficult for the manufacturers to produce it with the same quality and consistency as of old. All these factors led to a series of extraordinary difficulties in connection with time fuzes, such as irregular burning and a wholesale failure to burn at all; these difficulties were never completely overcome in practice, but they stimulated a much fuller investigation of the factors governing them, and have resulted in a far greater understanding of the physical behaviour of fuzes. As so often happens in the history of knowledge, urgent practical need led to scientific discovery.

The powder train fuze consists of one or more rings of highly compressed gunpowder forced into a metal groove. The ring is fired by a detonator at the moment the shell is accelerated in the barrel, and after a certain amount of it, adjustable beforehand, has been burnt it ignites a pellet which fires a second detonator which explodes the charge. The "fuze-setting," determining the length of powder to be burnt, and therefore the time of burning, is adjusted by turning the ring round an axis parallel to that of the shell. The gases produced by the combustion escape from a hole in the fuze, usually at the side, but sometimes in the nose. The position of this hole is of great importance, as will be shown below.

In a fuze at rest the time of burning is proportional to the length of powder burnt, and it has long been known that the rate of burning is a function of the atmospheric pressure. Very exact relations have been established between the pressure and the rate of burning under a variety of conditions, though their explanation is by no means clear, and some very interesting problems in the physical chemistry of combustion are provided by them. The gunpowder, of course, burns inside a closed ring, supplying its own oxygen, so that the effect of pressure is simply one of pressure as such. In the fuze fired in a shell from a gun the time of burning is by no means proportional to the length of powder burnt; usually the rate of burning is greatest at first (*i.e.* when the velocity of the shell is highest), decreasing gradually as the shell slows up until a more or less constant value is attained. In some fuzes, however, the rate of burning is least at first, increasing later on. Indeed, in some cases the same fuze may show one phenomenon when fired in one shell, and the opposite when fired in another. This complex relation between length of powder burnt and time of burning has received a complete explanation in the theory of the "dynamic pressure" at the escape holes. When a body moves rapidly through the air the pressure at any given point varies with the speed, and at any given speed varies from point to point of the shell. So completely does this theory explain the phenomena that an observed relation between "fuze-setting" and time of burning has been used even in the converse way to determine the pressure at a variety of points on the head of a shell moving at various speeds up to 1600 ft. per second. It is possible, of course, for the "dynamic pressure" to be a negative one—*i.e.* to be a "suction"—in which case, if it be sufficiently large, the powder may refuse to burn at all, and the shell will be "blind." This will be the case if the escape hole be too far back from the nose of the shell, or be under the lee of a projection on the fuze. It is necessary to take particular account of these factors in the design of the fuze body.

The scientific development of the theory of fuze burning dates largely from a trial carried out in the winter of 1916–17 at Portsmouth, in which a large number of fuzes of the same type and "lot" was fired to various heights up to 20,000 ft. in exactly similar shells, from five different 3-in. guns differing only in respect of their muzzle velocities. The results were very peculiar, and at first almost incredible; it was found that the effect of a given fall of atmospheric pressure in the upper air, whether in lengthening the time of burning or in producing a liability to irregularity and "blinds," was far greater in the case of a shell fired from a high-velocity gun than it was in the case of one fired from a low-velocity gun—quite independently of what its actual velocity might be at the moment considered. A given fuze in a given shell, moving at a given velocity, at a given reduced atmospheric pressure in the upper air, might be expected to burn at a definite fixed rate. It did not! The rate of burning depended on the previous history of the shell—viz. on the velocity with which it had left the muzzle of the gun. What effect could this previous velocity have left upon it? The mystery was so complete that one was clearly on the eve of a discovery. Various theories were put forward to account for it, such, for example, as that the shell "yawed" from its path to a degree varying from gun to gun, the "yaw" being supposed to affect the pressure at the escape holes, and therewith the time of burning. The true explanation, however, proved to be the hitherto unsuspected effect of "spin"—*i.e.* the angular velocity of the shell about its axis, and this factor has since proved practically the most important one in the behaviour of a powder train fuze. The shell, in order to secure stability in its flight, is given a high angular velocity by the rifling of the gun working on the copper driving-band. In all the guns employed (varying in velocity from 900 f.s. to 2500 f.s.) the twist of the rifling was 1 turn in 30 calibres—*i.e.* in 30 times 3 in. or 7½ ft. This gave angular velocities varying from 7200 to 20,000 revolutions per minute in the five guns. The angular velocity of a shell falls off comparatively slowly in flight, so that it could be regarded as approximately constant along the trajectory of each gun. The peculiar differences observed in the gun trials could be explained only as an effect of spin, and it was clearly necessary to carry out spinning trials on fuzes "at rest"—*i.e.* without forward velocity—to see if the effect of spin could be isolated. Such trials were carried out at speeds up to 30,000 r.p.m., and an enormous effect of spin was established. It was possible to double the time of burning of a fuze, or even to make it cease burning altogether, merely by spinning it. The effects of a fall of pressure also were exaggerated by spin, as was shown in the laboratory at University College, by spinning a fuze under reduced pressure.

The explanation of this effect of spin is interesting. It could not be due to any "dynamic pressure" effect at the escape holes, or to a centrifugal effect on the gases in the groove; these were investigated and found to be far too small. The real explanation is the centrifugal effect on the slag produced by the gunpowder in its combustion. When the spin is high the gunpowder, warmed, softened, and just ignited by the combustion of the previous layer, is "spun" outwards to the outer edge of the groove before it has had time properly to burn and to ignite the next layer; consequently, combustion is slower, and may fail altogether. The absence of any effect of spin in the case of a special powder giving no slag, as well as the fact that "blind" fuzes are found to have failed first on the *inside* edge of the ring, make it clear that the centrifugal effect on the slag is the prime cause of the trouble. At 30,000 r.p.m., a spin reached in fuzes fired from small guns, it is almost impossible to attain any accuracy at all. The rapid increase of fuze-trouble with spin is due to the fact that the centrifugal effect varies as the *square* of the spin.

One obvious means of avoiding the excessive effect of spin was to reduce the rifling of the gun and therewith the rotation of the shell. The possibility of doing this is strictly limited, as with too low a spin the shell becomes unstable. Two similar guns were rifled respectively 1 turn in 30 and 1 turn in 40 calibres, and in all respects the fuzes fired from the latter were found to behave more satisfactorily, thus confirming the results and predictions of laboratory trials. All similar guns were provided thereafter with the smaller rifling, with good effects.

Another factor affecting the behaviour of fuzes is their temperature. This effect, also previously unknown, is a smaller one, but by no means negligible. A fuze burns more quickly at a higher temperature, and allowance must be made for this in accurate firing. A curious phenomenon arises in connection with this. It was usual to test a fuze at rest as well as in the gun, and in the case of some long-burning fuzes at rest the fuze heats itself by its own combustion to such an extent that its time of burning is seriously decreased. This "self-heating" effect does not occur in a fuze fired from a gun, which is cooled by its passage through the air. Consequently, for accurate comparison with gun trials the fuze fired at rest must be cooled while it burns—*e.g.* by subjecting it to a rapid spray of water. This was actually done in later trials, the fuze being rotated in a closed box at any required spin and pressure, and subjected the while to a rapid jet of water to ensure the constancy of its temperature.

We may summarise as follows: The rate of burning of a fuze is a function of the total pressure at its escape holes, which is made up of the atmospheric pressure A and some function $f(v/V)$ of v its velocity and V the velocity of sound. It is a function also of the spin S and of the temperature T. Expressed mathematically, the rate of burning is equal to $F[\{A + \rho f(v/V)\}, S, T]$, where F is some complicated function of the three variables. It is easy to see that fuzes are likely to cause trouble when subjected to conditions, as they were in the late war, far exceeding in severity any under which they had previously been used; and to foretell that in the next war—if there be one—reliance will be placed mainly on clockwork fuzes unaffected by these various factors.

The Iridescent Colours of Insects.[1]

By H. ONSLOW.

III.—SELECTIVE METALLIC REFLECTION.

IN the two preceding articles various insects have been described and illustrated, which owe their principal iridescent effects to the colours of "thin plates" and to the diffraction of ribbed structures or "gratings." However, more than one physicist of repute has stated that most insect colours are due to selective metallic reflection. The arguments against this theory, as applied to scales, were considered in the first article; briefly, they are due to the facts that both reflected

[1] Continued from p. 183.