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PHYSICS OF ARMOUR PENETRATION*

During the World War I, armour was used as a protection against machine gun fire, fragments from artillery shells, and so on. The introduction of tanks and armoured-fighting vehicles in the battle-field, which may be defined as moving fortresses, giving armour protection and fire power to the crew, gave an impetus to the fundamental research into the mechanism of armour penetration and applied research, *i.e.* the development of new types of projectiles for armour penetration. The conventional method of armour penetration is an armour penetrating shot (A.P. Projectile) which consists of a hard tungsten carbide core having an envelope of mild steel and with or without an aluminium cap or ballistic cap. Early in the World War II, new types of projectiles based on the principle of " Hollow or Shaped Charge " appeared almost simultaneously in the armed forces of the major combatants.

Armour penetration is a subject of the first importance to the services for two reasons : they want to penetrate the armour of the enemy and they also want their own armour not to be penetrated. The purpose of this talk is to review the fundamental research into the mechanism of armour penetration. The armour penetrating projectiles, on the basis of Services jargon, are broadly classified into two headings :

Armour Penetration

A.P. Projectiles | " Shaped-Charge " Projectiles

Armour Penetration by A. P. Projectiles

The approach to the problem is a semi-empirical one. When such a projectile strikes a metallic target, it exerts huge pressure—say of the order of 20,000 atmospheres. The ductility, which is defined as the resistance to fracture, increases at a rapid rate when the pressures reach the neighbourhood of the pressures one is concerned with here. That is why under the impact, the armour does not fracture but the shot merely penetrates. There is ample experimental evidence that penetration in a given target depends on the kinetic energy of the projectile at the time it strikes the target. This energy has been taken up by the target and the result is a deep hole. Elementary considerations indicate that the penetration should depend on the strength of the target, which may be taken as proportional to the dynamic yield stress or static yield stress E. Let D represent the calibre of the projectile, m its weight, V the striking velocity and T the penetration in the armour plate. The resistance of the target or the retarding force per unit area is equal to $E \times T/D$. The principle of dimensional analysis indicates that $E \times T/D$ *i.e.* the force per

* Based on a talk given by Dr. D. S. Kothari, Scientific Adviser to the Ministry of Defence (Prepared by Shri Sampooran Singh, Defence Science Organisation).

unit area must be equal to mV^2/D^3 *i.e.* the energy per unit volume. Thi may be written as

$$\frac{mV^2}{D^3} = kE\left(\frac{T}{D}\right)^{\eta} \qquad \ldots\ldots\ldots\ldots (1)$$

where k and η are some constants. Experimentally η has been found to be equal to 2. From the design point of view m/D^3 for a projectile is approximately constant. Rewriting the Eq. (1) as

$$T = \sqrt{\frac{mV^2}{D^3} \times \frac{D^2}{kE}}$$

Putting $k' = \sqrt{\dfrac{m}{D^3kE}}$ in the above equation

$$T = k'VD \qquad \ldots\ldots\ldots\ldots (2)$$

If D is the calibre in inches, V the striking velocity in feet per second and T is the thickness of the armour penetrated in mm, then k' is equal to 1/40. It is also well known, then when an A.P. Projectile is penetrating a target and the target is just perforated, then the projectile has to travel a little more distance than the actual thickness of the target plate due to bulging of the back side. This bulging is assumed to be constant over the practical range of velocities.

When a shot strikes the armour at some other angle θ (measured as the angle with the normal to the surface of the plate and known as angle of attack or incidence), then the nose has to travel a distance $T/\text{Cos}\ \theta$. The correction for bulging the back side of the target is comparatively very small as compared to $T/\text{Cos}\ \theta$ hence

$$\frac{T}{\text{Cos}\ \theta} \backsim \frac{D \times V}{40} \qquad \ldots\ldots\ldots\ldots (3)$$

The above equation will be roughly applicable at small angles of attack.

The performance of an A.P. Projectile depends on the energy at the time when it is about to strike a target. The weight and calibre of a projectile are governed by the design considerations. To have more penetration by a given projectile the research is focussed to increase the muzzle velocity.

Armour Penetration by "Shaped-Charge" Projectiles.

The principle, that explosives having a cavity between the explosive and the target on detonation produce a deeper hole as compared to that given by the same weight of explosive in contact with the target, has been known for the last 150 years. It has been discovered only recently that if the cavity is lined by a thin metal, (known as liner) there is an enormous increase in penetration. During the War, the Germans developed Panzerschreck, Panzerfaust, etc. the British P.I.A.T. and the U.S.A. 2·36-in. Bazooka, which made use of this phenomena to perforate thick armour.

A fairly complete mathematical theory of this new phenomena has been published by Birkhoff, MacDougall, Pugh, and Taylor (J. Appl. Phys. *19*, 563, 1948). When a detonation wave sweeps from the apex to the base of a conical liner, it exerts enormous pressures on the surface of the liner, and the authors assume that under these conditions the strength of the liner is negligible and the metal behaves as a perfect fluid. The effect of the detonation wave at any element of the liner is to impart a velocity V_0 which bisects the angle between the perpendiculars to the original liner surface and to the collapsing liner surface. They have assumed V_0 to be constant from the apex to the base of a conical liner. An element m in the collapsing planes upon reaching the axis divides into two elements of masses m_j (going into the jet) and m_s (going into the slug), which proceed along the axis at the constant velocities V_j (Velocity of the jet) and V_s (velocity of the slug). On the basis of four independent relations, the equations of the conservation of mass, energy, momentum and Bernoulli equation, the authors have derived mathematical expressions for V_j, V_s, m_j and m_s. The velocity of the head of the jet is of the order of 5,000 to 10,000 meters/sec (*i.e.* 17 to 33 times the velocity of sound in air); while that of the tail end of the jet is about 2,000 meters/sec. The hydrodynamic theory of collapse does not explain satisfactorily the velocity gradient in the jet and issuing of the jet from the slug long after the collapse of the conical liner is complete (known as 'after-jet' effect)*. The collapse of the liner at different stages has been actually observed by X-ray flash photography.

When this high velocity jet impinges upon a target, it exerts pressures of about a quarter million atmospheres. Under this high pressure, the metal behaves as a semi-fluid mass and the penetration is achieved by lateral expansion of the target material, the main displacement of the material being in a radial direction. Birkhoff et al have assumed the strength of the target to be negligible and have concluded that the depth of penetration by a jet into a given target is independent of the velocity of the jet and depends upon its length and density. For a given jet against different targets, the depth of penetartion varies inversely as the square root of the density of the target. The penetration P of a jet is given by the following expression

$$P=L\sqrt{\lambda\rho j/\rho T} \qquad \ldots\ldots 4$$

where L is the length of the jet, $\lambda\rho_j$ its mass per unit volume and ρ_T the density of the target. λ is a parameter which depends on the nature of the jet and equals one for a fluid jet and two for a fragment jet.

The theory does not explain some experimental observations e.g. the difference of penetration in armour and mild steel, penetration in lead and mild steel. Pack and Evans (Proc. Phys. Soc. B. *64*, 298, 1951 and B. *64*, 303, 1951) have explained the above two observations by taking into consideration the strength of the target. The authors have also divided the action of the jet into two stages, the first stage is the consumption of the whole jet by the target

* In a recent paper, Pugh, Eichelberger, and Rostoker (J. Appl. Phy. *23*, 532, 1952), by assuming a variable instead of a constant collapse velocity for the walls of the conical liner, have satisfactorily explained the velocity gradient in the jet and the "after-jet" effect.

and second stage is the after flow of the target and have denoted it as the secondary penetration. They have taken the secondary penetration to be equal to the radius of the crater (measured near the bottom of the hole).

Birkhoff et al showed that the penetration by a jet from a conical liner at first increased and then decreased with the increase of " stand off ". They have explained this by considering the lengthening of the jet due to the velocity gradient and by assuming that there is a radial spread which is linear with " standoff " and symmetrical along the axis. The momentum of the jet has been found to be constant and independent of " standoff ". As a protection against the attack by " Shaped-Charge " projectiles, the Spaced-Armour, Plastic-Armour, Spikes, etc. have been tried, but Spaced-Armour has been found to be most promising.

When a " Shaped-Charge " projectile is spin-stabilized during its flight, its penetration is greatly reduced, hence such a projectile is fin-stabilized and consequently the range is less and accuracy is poor. Attempts are being made to combine the penetrating power of a bazooka, and range and accuracy of a rifled weapon. Just as the introduction of fire-arms brought about the extinction of the armoured knights because a bullet could easily penetrate the kind of armour that the knights could put on ; similarly " Shaped-Charge " projectiles having the range and accuracy of a rifled weapon will seriously affect the tactical use of armour in the battle-field.