Ballistics – experiments and modelling

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ABSTRACT

The term ballistics is commonly divided into four sub-areas: internal ballistics, transitional ballistics, external ballistics and terminal ballistics. This paper deals with the area of "terminal ballistics". It is mainly focused on the interaction of a threat to armour material.

At first the most important kinds of threats are presented. Their effect on different armour configurations will be analysed. Therefore it is necessary to know the behaviour of the materials used for different threats and armour designs. The impact velocity is of particular importance, because it determines the penetration mechanism and thereby the metal or alloy to use as armour. The concept of materials for armour have to be evaluated by DoP (Depth of Penetration) and V_{50} (Ballistic Limit) tests. It will be shown how the test configuration and the used reference materials influence strongly the parameters. The modelling of ballistic results is also a topic covered in this paper.

Great attention will be paid to the faults of armour materials due to impact loading. The failure types of very hard materials are brittle cracking and for ductile materials, adiabatic shear banding. By far the largest amount of armour materials are ductile, so adiabatic shear banding is the most important failure mechanism in the field of terminal ballistics.

INTRODUCTION

The term ballistic has been cut into 4 subfields and these are:

A **Internal Ballistic**

B **Transitional Ballistic**

C **External Ballistic**

D **Terminal Ballistic**

The **internal ballistic** is concerned itself with the process inside the gun barrel. It studies the motion of a projectile from the time its propellant's igniter is initiated until it exits the barrel. The energy to accelerate a projectile is imparted by the pressure of the gases of burning powder, which serves as propellant. There are hundreds of powders in existence depending on the application. Two well known powders are nitrocellulose (single-based propellants) and double-base propellants. The nitrocellulose or guncotton is a smokeless powder. To increase its energy nitroglycerin can be added up to 50% and then it's called double-base propellant. A high peak pressure alone does not produce higher velocities. It is the entire duration of a bullet or projectile, which has to be considered to achieve maximum performance [1- 3].

The heat produced from the burning powder in combination with accelerating projectiles leads to the erosion of the inside of a barrel. A subfield of internal ballistic is dealing with coatings on the inside in order to minimize erosion and to shield the gun barrel alloy from strong heating up.

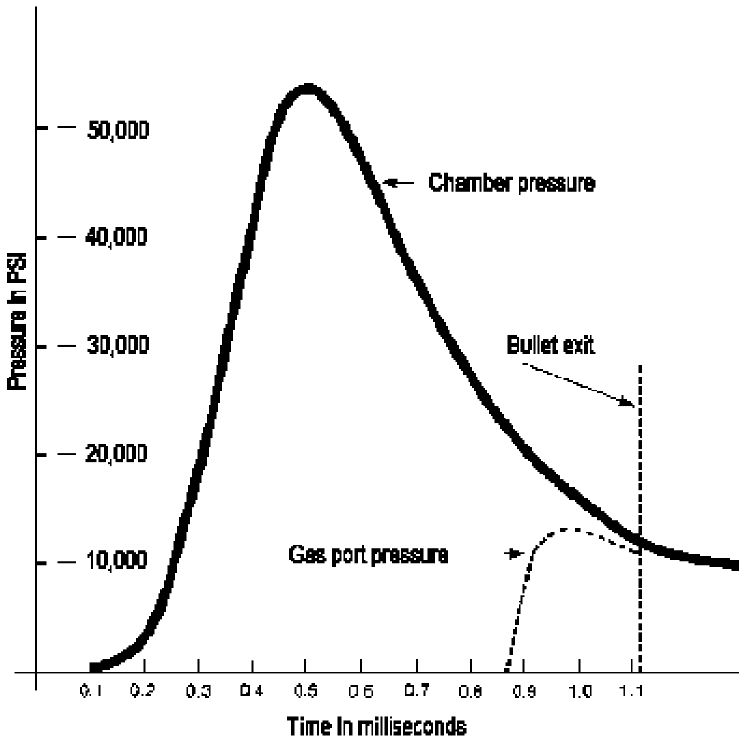

Figure 1: The graph shows a representative pressure curve of a typical cartridge. The peak pressure rises quickly and then tapers off. The location of the peak pressure and its shape is determined by the burning characteristic of the powder used and the loading density.

To stabilize the bullets in the airflow gyroscopically by spinning nearly all small bore firearms, with the exception of shotguns, have rifled barrels. The rifling imparts a spin on the bullet, which keeps it from tumbling in flight. The rifling is usually in the form of sharp edged grooves cut as helices along the axis of the bore, anywhere from 2 to 16 in number. The areas between the grooves are known as lands.

Another system, polygonal rifling, gives the bore a polygonal cross section. Polygonal rifling is not very common. The companies that use polygonal rifling claim greater accuracy, lower friction, and less lead and/or copper buildup in the barrel. Traditional land and groove rifling is used in most competition firearms, however, so the advantages of polygonal rifling are unproven

Smoothbore/Fin-Stabilized: In modern artillery smoothbore tubes have been used mostly by mortars. These projectiles use fins in the airflow at their rear to maintain correct orientation. The primary benefits over rifled barrels is reduced barrel wear, longer ranges that can be achieved (due to the reduced loss of energy to friction and gas escaping around the projectile via the rifling) and larger explosive cores for a given caliber artillery due to less metal needing to be used to form the case of the projectile because of less force applied to the shell from the non-rifled sides of the barrel of smooth bore guns.

Transitional ballistic, also known as **intermediate ballistics** [4**]** is the study of a projectile's behavior from the time it leaves the muzzle until the pressure behind the projectile is equalized, so it lies between internal ballistics and external ballistics (fig. 2).

Transitional ballistics is a complex field that involves a number of variables that are not fully understood; therefore, it is not an exact science [5]. When the bullet reaches the muzzle of the barrel, the escaping gases are still, in many cases, at hundreds of atmospheres of pressure. Once the bullet exits the barrel, breaking the seal, the gases are free to move past the bullet and expand in all directions. This expansion is what gives gunfire its explosive sound (in conjunction with the sonic boom of the projectile), and is often accompanied by a bright flash as the gases combine with the oxygen in the air and finish combusting.

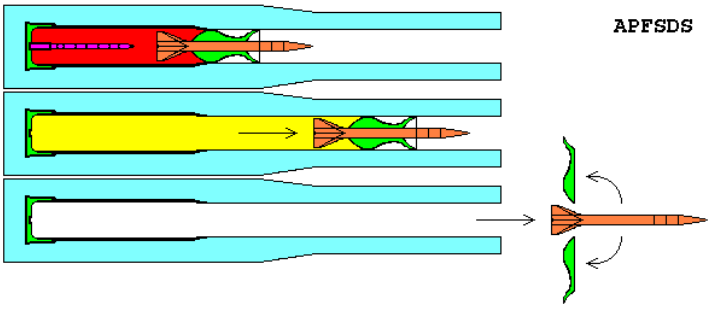

Figure 2: It shows the acceleration of an anti tank long rod penetrator and how it leaves the muzzle. The sabot used here is called a spindle sabot. After leaving the muzzle the penetrator has to separating from it. APFSDS = Armour Piercing Fin Stabilized Discarding Sabot.

External ballistics is the part of the science of ballistics that deals with the behaviour of a non-powered projectile in flight. External ballistics is frequently associated with firearms, and deals with the behaviour of the bullet after it exits the barrel and before it hits the target.

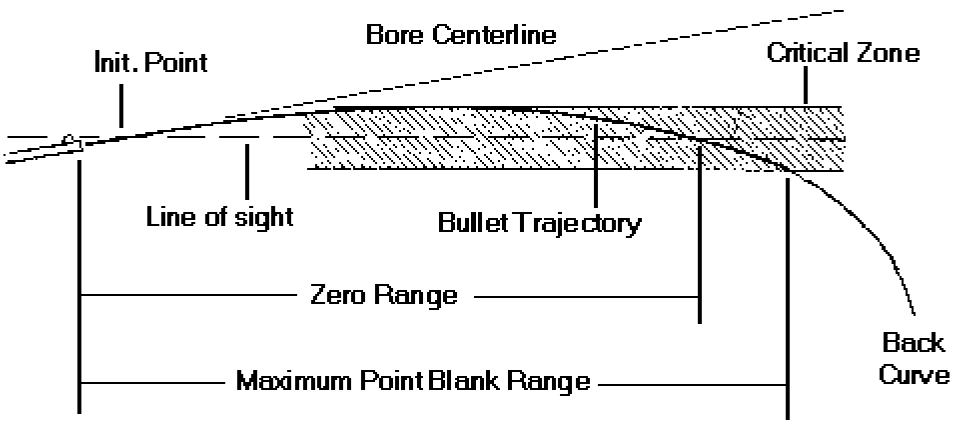

Figure 3: The bore's angle in relation to the line of sight is exaggerated in this drawing for clarity

When in flight, the main forces acting on the projectile are gravity, drag, and if present, wind. Gravity imparts a downward acceleration on the projectile, causing it to drop from the line of sight. Drag, or the air resistance, decelerates the projectile with a force proportional to the square of the velocity. Wind makes the projectile deviate from its trajectory. During flight, gravity, drag, and wind have a major impact on the path of the projectile, and must be accounted for when predicting how the projectile will travel [6]. Two methods can be employed to stabilize non-spherical projectiles during flight:

Projectiles like arrows or sabots like the M829 Armor-Piercing, Fin-Stabilized, Discarding Sabot (APFSDS) achieve stability by forcing their center of pressure (CP) behind their center of gravity (CG) with tail surfaces. The CP behind the CG condition yields stable projectile flight, meaning the projectile will not overturn during flight through the atmosphere due to aerodynamic forces.

Projectiles like small arms bullets and artillery shells must deal with their CP being in front of their CG, which destabilizes these projectiles during flight. To stabilize such projectiles the projectile is spun around its longitudinal (leading to trailing) axis. The spinning mass makes the bullet's length axis resistant to the destabilizing overturning torque of the CP being in front of the CG.

Terminal ballistics, a sub-field of ballistics, is the study of the behavior of a projectile when it hits its target [8]. Terminal ballistics is relevant both for small caliber projectiles as well as for large caliber projectiles (fired from artillery). The study of extremely high velocity impacts is still very new and is as yet mostly applied to spacecraft design.

The interaction between bullet/projectile and target is including in this paper the materials for both the threat and also the protective armour, whereas the main focus lies on protective materials for armoured vehicles. Materials like gelatin or ballistic soap as it is in use in wound ballistic for simulating a human body are excluded.

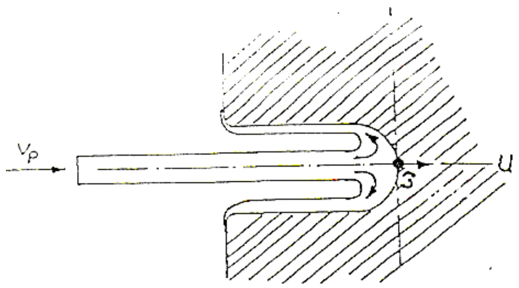

Figure 4: Hydrodynamic penetration of a long rod (kinetic energy projectile) in armour material.

In figure 4 is schematically presented how a long rod projectile penetrates an armour material. Long rods were very important during the cold war to defend attacks of main battle tanks.

THREADS FOR ARMOURED VEHICLES

Threads for armoured vehicles are:

A KE-projectiles or bullets

B Shaped charges

C EFP (Explosively Formed Penetrator)

D Fragments

A: Armour piercing (AP) bullets possess a hard core consisting mainly of strongly hardened steel (HRc = 60 – 64, ρ = 7.85 g/cm^3). Specially designed models are of WC having an increased hardness and a density ρ = 13.5 – 15 g/cm^3. So **t**he bullets are not deformable the mechanic is the penetration is that of a rigid body. The impact velocity of firearms does not exceed 800 or 1000 m/s. Machine guns are reaching 1300 m/s. The kinetic energy of bullets is reaching in the maximum 10^3 - 10^4 J.

What bullets end up (figure 6) being is truly a compromise between aerodynamics, manufacturing, materials and interior ballistic considerations (minimizing in-bore yaw). Consider the penetration with different nose shapes in figure 7 it is clear that the ogive-nose rod is the most efficient one since its final penetration depth is the highest, while the flat-nose rod is the less efficient. The geometry of a tangent ogive is shown in figure 8.

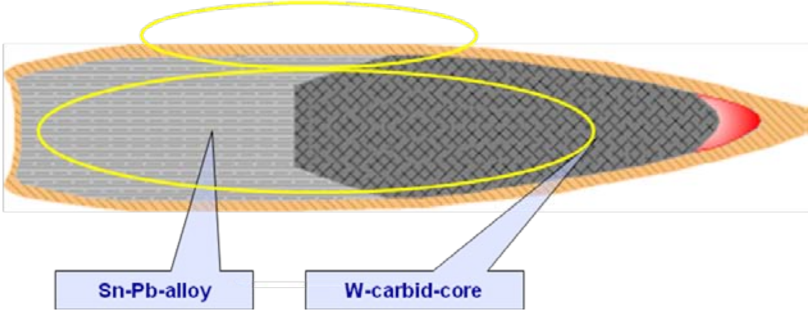

Figure 5: Draft of AP bullet having ideal weight distribution (patent RUAG Ammotech)

Figure 6: Some examples of bullets with different nose shapes

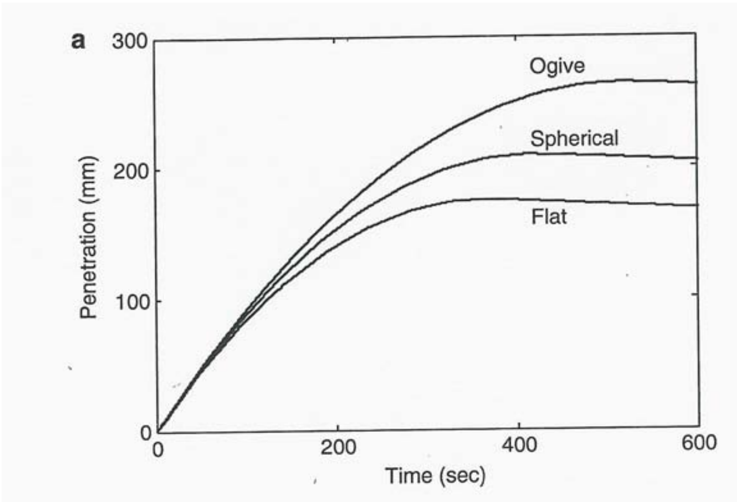

Figure 7: Simulation results of penetration for different nose shaped bullets [9]

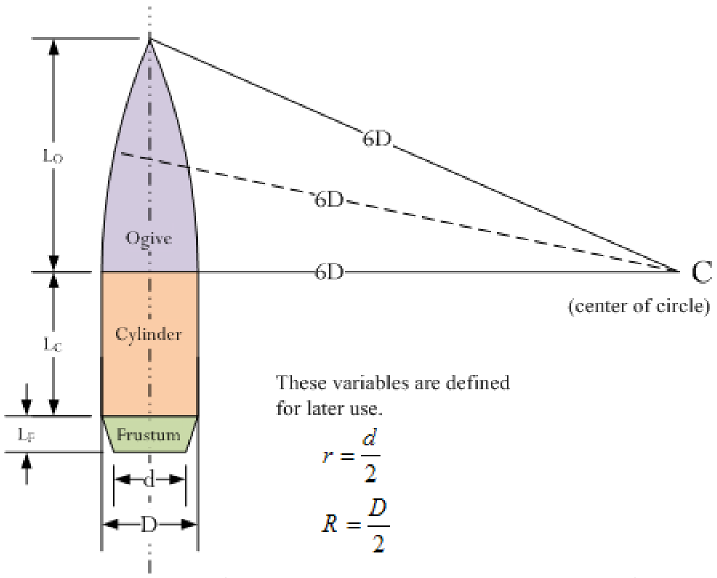

Figure 8: Descriptive Geometry of a Spitzer Bullet (Tangent Ogive with Radius of 6 Diameters)[10].

One of the most effective threats to defeat main battle tanks are kinetic energy (KE) or long-rod penetrators. Penetrators are made of high strength, high density materials, such as W sintered alloy or depleted U, having densities near 18 g/cm^3 and moderate hardness, good toughness and ductility. At ordnance velocity they yield a kinetic energy in excess of 10^6 J and creating high energy density per unit area of a target impacted. A high L/D aspect ratio exceeds 30:1 (fig. 9). The calibers used for long rods ranging depending on their size from 20 mm up to 140 mm. The impact velocity amounts from 1300 to >1600 m/s.

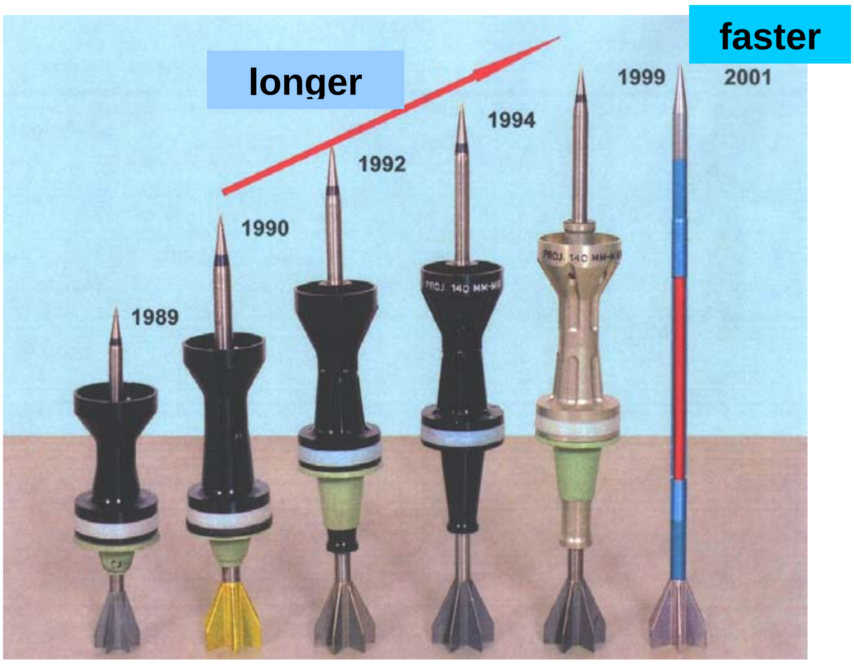

Figure 9: The photograph shows the development of the L/D aspect ratio. From the year 2000 on the focus is on increasing impact velocity.

B: Further effective threat against armoured vehicles inclusive main battle tanks is the shaped charge (fig. 10, HL). The particle jet exceeds a velocity of 9000 m/s and is resulting in hydrodynamic penetration. A considerable compression during penetration is far beyond of materials strength that they not taken in consideration. Another version of shaped charges is the hemispherical charge (fig. 10, Hemi) characterized by a thicker jet. The jet of a hemispherical charge is not as fast as that of a shaped charge, but it is more stable.

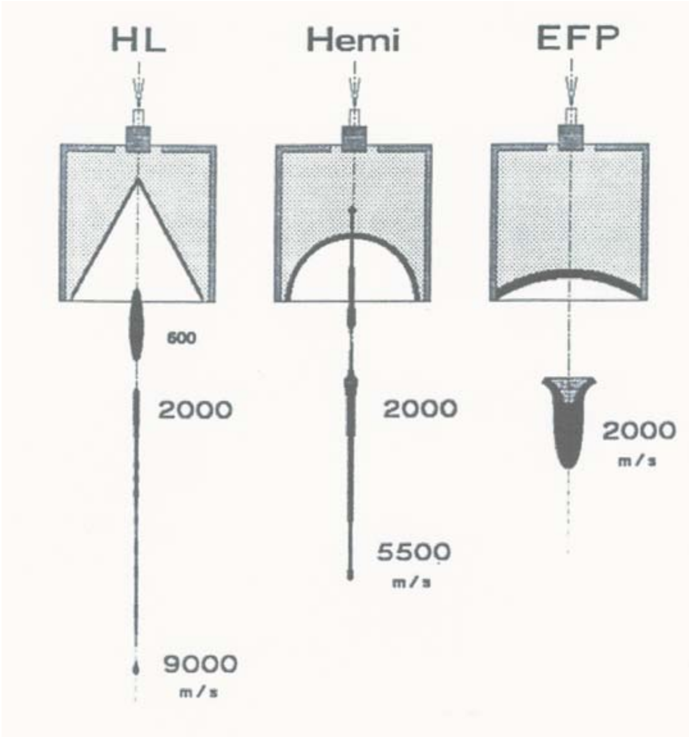

Figure 10: Schematic description of conical chaped charge (CL), hemispherical shape charge (HEMI) and explosively formed projectile (EFP). The effective mass (of jet) for calibre 100 mm amounts to 85 g (CL), 175 g (HEMI) and 350 g (EFP). Key features are an increased depth of crater (CL), an increased mass of jet (HEMI) and an increased fighting distance (EFP).

C: Figure 10 shows also schematically an explosively formed penetrator (fig. 10, EFP) and fig. 11 the time-evolved formation. The impact velocity is ranging from 1000 m/s up to 2000 m/s. Materials used have to be plastically deformable, so Cu is a frequently used metal. Its kinetic energy leads to hydrodynamic penetration. It is supposed that material strength influences the penetration.

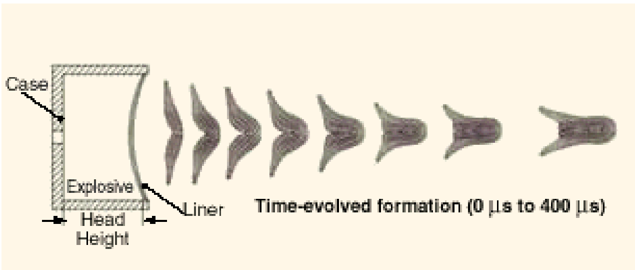

Figure 11: The formation of an EFP

D: Fragments are known from Fragmentation mines, which project hundreds of metal fragments, showering the victim with deep wounds. Bounding fragmentation mines are more powerful versions: they spring up about 1 meter and then explode, firing metal fragments to a large radius. The impact velocity of these fragments is relatively small with about 300 or 400 m/s. Fragments are also present in IED's (Improvised Explosive Device). The impact velocity of IED fragments is reaching 1000 m/s and may excess it. Hydrodynamic penetration occurs, but it is supposed that it depends also on the strength.

In the recent three decades conventional military action diminish and unconventional warfare by guerrillas or commando forces and terrorists attacks rise up. The most lethal weapon they are using is IED. An

IED, also well known as homemade bomb, has five components: a switch (activator), an initiator (fuse), container (body), charge (explosive), and a power source (battery). An IED designed for use against armored targets such as personnel carriers or tanks will be designed for armour penetration, by using either a shaped charge or an explosively formed penetrator. IEDs are extremely diverse in design, and may contain many types of initiators, detonators, penetrators, and explosive loads. Antipersonnel IEDs typically also contain fragmentation-generating objects such as nails, ball bearings or even small rocks to cause wounds at greater distances than blast-pressure alone could.

a)

b)

Figure 11: a) IED in Iraq. The concave copper shape on top is an explosively formed penetrator. **b)** Homemade half shell

Figur 12: Homemade EFP

Figure 13 a)

Figure 13 a) and b): Ammunition rigged for an IED discovered by Iraqi police in Baghdad

In figures 11 to 13 are shown some examples of IED's as they could be found in critical countries like Iraq and Afghanistan. Figure 14 shows fragments as they are present in IED's. The impact that an actual IED fragment may have on a vehicle varies based on speed and orientation of impact.

Figure 14: Fragments used in IED's

In order to provide a consistent means of data comparison Fragment Simulator Projectile (FSP), which replicates materials present in IED's, are used. The FSP is a U.S. and NATO standard test projectile used by other Army laboratories (fig. 15).

Figure 15: Fragment Simulator Projectiles, defined in MIl-P-46593A, made of 40 NiCrMo 84 (1.6562), HRC 30. From 0.237 g / 3.25 mm to 13.4 g / 12.9 mm

AMMUNITION FOR LAW ENFORCEMENT AUTHORITIES

Conventional full metal jackets do not meet all the requirements set on modern combat ammunition for law enforcement authorities. Due to their low energy transfer in the target, they easily penetrate through soft targets exposing bystanders to the risk of being hit by the shot. The increasing tendency towards violence in urban areas calls for special ammunition, able to stop an aggressor without permanently injuring him. It is essential that the bullets are able to punch holes in tires so that the air can escape quickly. It takes several minutes for a tire to go flat when hit with a full metal jacket bullet, but less than 10 seconds for the air to escape with a deformation bullet. Deformation bullets (fig. 16), although they consist of solid material, have no more residual energy than conventional full metal jacket lead core bullets due to the optimized bullet shape.

Figure 16: Deformation ammunition 9 x 19 ACTION 4 SXF [11]

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