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Hydrodynamic Penetration

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Hydrodynamic Penetration

- What is Hydrodynamic Penetration?
- Which Munitions use Hydrodynamic Penetration?
- How does Hydrodynamic Penetration Work?
- Technology of Munitions utilising Hydrodynamic Penetration.



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Hydrodynamic Penetration

What is
Hydrodynamic Penetration?

Hydro

↓

Water/Fluid

dynamic

↓

Moving/Speed

Penetration

↓

Poking Holes In Things

 **Hitting something so Hard that it Flows like a Fluid and Moves Aside to make a hole.**

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Hydrodynamic Penetration

Which Munitions use Hydrodynamic Penetration?

- Kinetic Energy Penetrators  1 - 2 km/s
- Explosively Formed Projectiles  2 - 4 km/s
- Shaped Charges  5 - 10 km/s



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Hydrodynamic Penetration

How does Hydrodynamic Penetration Work?

All materials have characteristics that describe how they respond to different stimuli, such as **Stress** and **Strain**.

Hydrodynamic Penetration occurs when a material is **Stressed** beyond the compressive **Strain** that it can sustain, causing it to **flow like a fluid**.



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Hydrodynamic Penetration

Mechanism:

The 'jet' approaches the target at 1 - 10 Km per second:



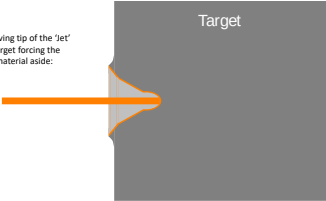


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Hydrodynamic Penetration

Mechanism:

The fast moving tip of the 'jet' hits the target forcing the target material aside:



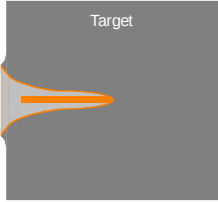
Target

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Hydrodynamic Penetration

Mechanism:

The 'jet' is 'used up' and coats the inside of the hole as it penetrates:



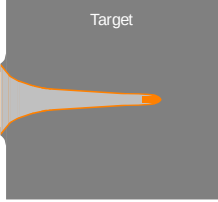
Target

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Hydrodynamic Penetration

Mechanism:

The slower rear end of the 'jet' delivers less energy into the target, making a narrower hole:

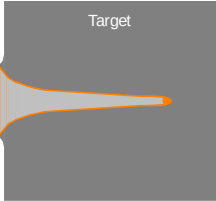


Target

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Hydrodynamic Penetration

Mechanism:
The whole 'jet' is gradually
'used up' as it penetrates
the target:



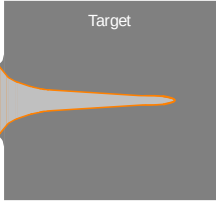
Target



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Hydrodynamic Penetration

Mechanism:
Until the whole of the 'jet'
has been 'used up' and
penetration stops:



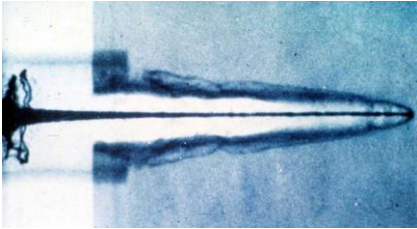
Target



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Hydrodynamic Penetration

This is a Flash X-Ray Showing A Jet Penetrating A Target





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Hydrodynamic Penetration

Strain = Ratio of the amount of deformation experienced by the body in the direction of force applied to the initial sizes of the body.

$$\epsilon = \delta l / L$$

Where;

ϵ is strain due to stress applied

δl is changed in length

L is the original length of the material.



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Hydrodynamic Penetration

Stress = The force applied per unit area.

$$\Sigma = F / A$$

Where;

Σ is stress applied,

F is force applied,

A is the area of force applied

Stress is measured by unit N/m^2



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Hydrodynamic Penetration

Stress = The force applied per unit area.

$$\Sigma = F / A$$

Therefore:

- Same Force over a Smaller Area = Greater Stress
- Larger Force over Same Area = Greater Stress



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Hydrodynamic Penetration

Greater Penetration (Hydrodynamic or not) is achieved by Projectiles with Smaller Diameter to Length Ratios.



Same Mass and Velocity
= Same Impact Force



 The projectile with the smaller diameter will penetrate further because the same Force is applied over a smaller area, thus increasing the Stress experienced by the target material, resulting in deeper penetration.

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Hydrodynamic Penetration

Projectile Length is even more critical in Hydrodynamic Penetration.

An equation that describes Hydrodynamic Shaped Charge Penetration was in use in the 1940's, this equation was derived from Bernoulli:

$$L_p = L_j \left(\frac{\rho_j}{\rho_T} \right)^{\frac{1}{2}}$$

Where;
 L_p = Length of Penetration, L_j = Length of Jet, ρ_j = Density of Jet, ρ_T = Density of Target

 Note: Velocity does NOT feature in this equation.

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Hydrodynamic Penetration

$$L_p = L_j \left(\frac{\rho_j}{\rho_T} \right)^{\frac{1}{2}}$$

Let Us Assume:

- A Copper Jet - therefore ρ_j = Density of Jet = 8.9 g/cc
- A Mild Steel Target - therefore ρ_T = Density of Target = 7.8 g/cc

$$L_p = L_j \left(\frac{8.9}{7.8} \right)^{\frac{1}{2}} \longrightarrow L_p = L_j (1.141)^{\frac{1}{2}} \longrightarrow L_p = L_j \times 1.068$$

 It is now easy to see that the jet/projectile length is proportional to the achieved penetration.

The longer the jet/projectile the deeper the penetration.

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Hydrodynamic Penetration

$$L_p = L_j \left(\frac{\rho_j}{\rho_T} \right)^{\frac{1}{2}}$$

With Different Materials:

- A Depleted Uranium Jet - therefore ρ_j = Density of Jet = 19.0 g/cc
- An Aluminium Target – therefore ρ_T = Density of Target = 2.7 g/cc

$$L_p = L_j \left(\frac{19.0}{2.7} \right)^{\frac{1}{2}} \longrightarrow L_p = L_j (7.037)^{\frac{1}{2}} \longrightarrow L_p = L_j \times 2.653$$


Higher Density Jet and/or Lower Density Targets deliver deeper penetrations from the same jet length.

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Hydrodynamic Penetration

$$L_p = L_j \left(\frac{\rho_j}{\rho_T} \right)^{\frac{1}{2}}$$

True Hydrodynamic Penetration is independent of Velocity, as there is no Velocity term within the equation.

But ...

At velocities below 4 km/s a velocity dependant Hydrodynamic Efficiency Factor needs to be added to the equation:

$$L_p = \eta L_j \left(\frac{\rho_j}{\rho_T} \right)^{\frac{1}{2}}$$

Where: η = Hydrodynamic Efficiency



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Hydrodynamic Penetration

$$L_p = \eta L_j \left(\frac{\rho_j}{\rho_T} \right)^{\frac{1}{2}}$$

The work of Hohler and Stip in 1977 identified the need for this Efficiency Factor at velocities below 4 km/s.

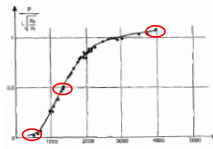
They fired tungsten alloy rods, with a length over diameter ratio of 32 to 1, into steel targets at various velocities up to 5 km/s (5 mm/ μ s).

The experimental results show that the efficiency of Hydrodynamic Penetration is affected by velocity.

There being effectively zero hydrodynamic penetration below 0.5 km/s (0.5 mm/ μ s).

At approx. 1.7 km/s (1.7 mm/ μ s) the results show a 50% hydrodynamic Efficiency.

The curve turns and levels off at 4.0 mm/ μ s where 100% hydrodynamic efficiency is achieved.



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Hydrodynamic Penetration

Hydrodynamic Efficiency:

		Efficiency
• Kinetic Energy Penetrators		1 - 2 km/s 25% - 75%
• Explosively Formed Projectiles		2 - 4 km/s 75% - 100%
• Shaped Charges		5 - 10 km/s 100%

 Therefore Shaped Charge Jets can be expected to penetrate further than EFP's or KE Penetrators of the same length.

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Hydrodynamic Penetration

Technology of Munitions utilising Hydrodynamic Penetration.

- Kinetic Energy Penetrators 
- Explosively Formed Projectiles 
- Shaped Charges 

 **Length Really Does Matter**

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Hydrodynamic Penetration

Kinetic Energy Penetrators:



- APFSDS – Armour Piercing Fin Stabilised Discarding Sabot.
- Long, thin, dart like projectiles made of high density metal:
 - Tungsten
 - Depleted Uranium !
- Not the right shape for Firing from Tank Guns.
- UK Tank Guns are rifled to impart spin and stabilise shells.
- APFSDS are **NOT** spin stabilised – Have tail fins for drag stabilisation.





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Hydrodynamic Penetration

Shaped Charges:

Many industries use Shaped Charges for different applications, there are two main configurations that are used:

Conical Shaped Charges

Used to create single deep circular holes. Their uses include; Anti-Tank Weapons and Oil Well Perforators .



Linear Cutting Charges

Used to create a cutting effect as the name suggests. Their uses include; the severance of structural members, pipes, plates, re-enforcing, etc. - often used in Demolitions and Bomb Disposal.



Shaped Charges
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Hydrodynamic Penetration

Shaped Charges:

Both of these configurations share the same cross-sectional features:

A Triangular Liner
Backed with Explosive



Shaped Charges
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Hydrodynamic Penetration

Shaped Charges:

We will concentrate on the Anti-Tank role of Shaped Charges.

In military circles Shaped Charges are often referred to as HEAT rounds.

This has nothing to do with the temperature at which they operate.

H.E.A.T. stands for **H**igh **E**xplosive **A**nti **T**ank

They do get warm as they function, but only up to about 400 °C, copper doesn't melt until 1085 °C and steel at 1450 °C.

So HEAT rounds **DO NOT** melt their way through their target.



Shaped Charges
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Hydrodynamic Penetration

Shaped Charges:

The Munroe Effect

As you might expect, detonating an explosive charge against the metal surface of a solid target will form a dent or crater:



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Hydrodynamic Penetration

Shaped Charges:

The Munroe Effect

While experimenting with compressed charges of Nitro-cellulose in 1888, Charles Edward Munroe noticed that the manufacturers name, which was pressed into the block, was reproduced on the targets surface:



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Hydrodynamic Penetration

Shaped Charges:

The Munroe Effect

Further experimentation lead him to discover that a raised point
Instead of a depression in the end of an explosive charge
created a crater with a similar raised point at its centre:



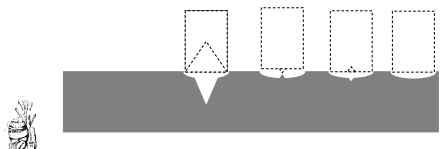
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Hydrodynamic Penetration

Shaped Charges:

The Munroe Effect

His investigations revealed that the larger the cavity,
the larger the cutting effect.



The diagram shows a grey rectangular block representing a target material. On the left side of the block, a dashed outline of a shaped charge is shown. An arrow points from the charge to a deep, narrow, V-shaped cavity that has been formed in the surface of the block. To the left of the block, there is a small icon of a dynamite stick with a lit fuse.

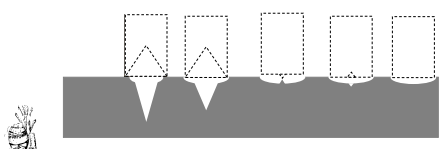
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Hydrodynamic Penetration

Shaped Charges:

The Munroe Effect

Putting a metal liner inside the cavity increases
the depth of penetration:



The diagram shows a grey rectangular block representing a target material. On the left side of the block, two dashed outlines of shaped charges are shown. Arrows point from each charge to a deep, narrow, V-shaped cavity that has been formed in the surface of the block. To the left of the block, there is a small icon of a dynamite stick with a lit fuse.

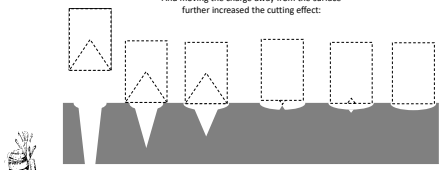
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Hydrodynamic Penetration

Shaped Charges:

The Munroe Effect

And moving the charge away from the surface
further increased the cutting effect:



The diagram shows a grey rectangular block representing a target material. On the left side of the block, three dashed outlines of shaped charges are shown at different distances from the surface. Arrows point from each charge to a deep, narrow, V-shaped cavity that has been formed in the surface of the block. To the left of the block, there is a small icon of a dynamite stick with a lit fuse.

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Hydrodynamic Penetration

Shaped Charges:

Configuration



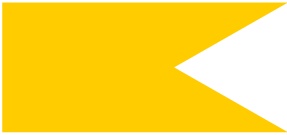
Firstly we take a solid explosive charge.

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Hydrodynamic Penetration

Shaped Charges:

Configuration



A hollow void is formed in one end of the charge.

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Hydrodynamic Penetration

Shaped Charges:

Configuration



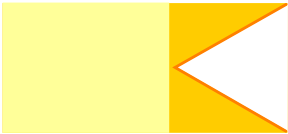
A close fitting metal liner is inserted into the void.

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Hydrodynamic Penetration

Shaped Charges:

Detonation



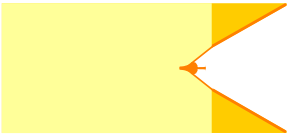
For simplicity, these examples will show a 'Plane Wave' detonation.
The detonation front travels down the charge.

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Hydrodynamic Penetration

Shaped Charges:

Detonation



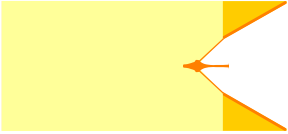
The detonation front meets the metal liner.

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Hydrodynamic Penetration

Shaped Charges:

Detonation



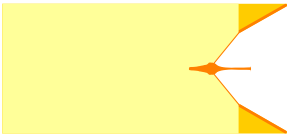
And forces the metal towards the centre of the hollow.

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Hydrodynamic Penetration

Shaped Charges:

Detonation



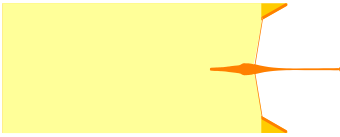
And forces the metal towards the centre of the hollow.

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Hydrodynamic Penetration

Shaped Charges:

Detonation



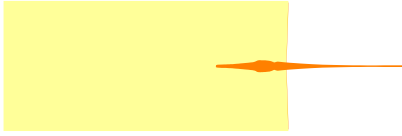
Forming a 'jet' that can travel as fast as 10 Km per second.

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Hydrodynamic Penetration

Shaped Charges:

Detonation



Energy from the explosive imparts momentum to the liner material.

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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching



Making the liner flow into the 'jet', even after all of the explosive has been consumed.

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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching



Because the tip of the 'jet' is travelling faster than the rear, the 'jet' stretches, becoming longer.

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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching



And longer.

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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching

This is a Flash X-Ray of a Shaped Charge Jet:



If we overlay an outline of the previous slide, you can see that the drawn examples are realistic.

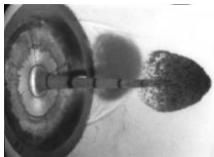
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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching

This image was created by a high powered laser illumination technique that allows the light produced by the explosive detonation, to be filtered out.



This is a photograph of the jet produced by the detonation of a shaped charge. The jet is shown in the process of stretching and is surrounded by a cloud of gas and debris. The jet is the result of the explosive material being forced into a high velocity jet by the detonation of the shaped charge.

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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching



The slowest moving, rear portion of the 'jet' is called the 'slug' and only travels at a few hundred meters per second.

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Hydrodynamic Penetration

Shaped Charges:

Jet Flight & Stretching

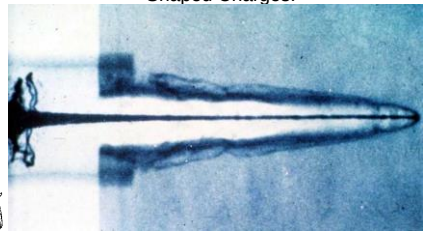


As the 'jet' continues to stretch, it breaks away from the slower moving 'Slug' (the 'Slug' is sometimes referred to as the 'Carrot') the fast moving 'jet' flies towards the target and is followed by the slower 'Slug'.

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Hydrodynamic Penetration

Shaped Charges:



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Hydrodynamic Penetration

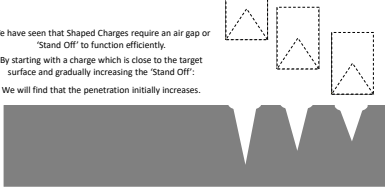
Shaped Charges:

Effect Of Stand Off

We have seen that Shaped Charges require an air gap or "Stand Off" to function efficiently.

By starting with a charge which is close to the target surface and gradually increasing the "Stand Off":

We will find that the penetration initially increases.



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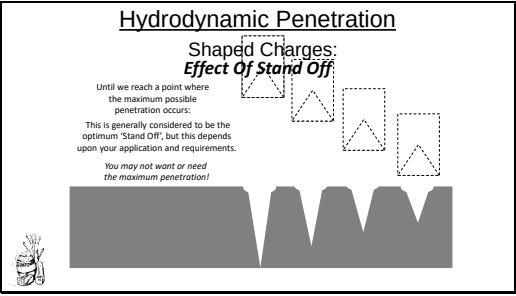
Hydrodynamic Penetration

Shaped Charges: *Effect Of Stand Off*

Until we reach a point where the maximum possible penetration occurs:

This is generally considered to be the optimum 'Stand Off', but this depends upon your application and requirements.

You may not want or need the maximum penetration!

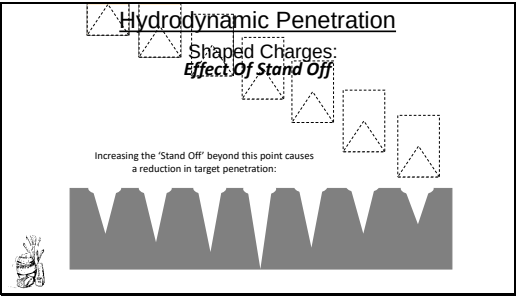


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Hydrodynamic Penetration

Shaped Charges: *Effect Of Stand Off*

Increasing the 'Stand Off' beyond this point causes a reduction in target penetration:



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Hydrodynamic Penetration

Shaped Charges: *Effect Of Stand Off*



The reason for this is that, given enough space ('Stand Off') a Shaped Charge 'jet' will continue to stretch.



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Hydrodynamic Penetration

Shaped Charges:
Effect Of Stand Off



By examining a small section of the 'jet' we can see the effect this has.

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Hydrodynamic Penetration

Shaped Charges:
Stretching of the 'Jet'



The 'jet' continues to stretch.

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Hydrodynamic Penetration

Shaped Charges:
Stretching of the 'Jet'



Until the Dynamic Yield Strength of the 'jet' material is reached, when it begins to 'neck'.

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Hydrodynamic Penetration

Shaped Charges:
Stretching of the 'Jet'

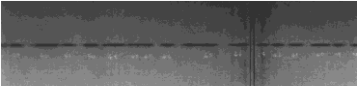


Eventually it breaks up into a number of smaller particles.

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Hydrodynamic Penetration

Shaped Charges:
Stretching of the 'Jet'





This is a Flash X-Ray Radiograph showing the particles as a Shaped Charge 'jet' breaks up.

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Hydrodynamic Penetration

Shaped Charges:
'Jet' Break Up & Particle Drift



Once the 'jet' has broken up, the individual particles will, unless the 'jet' is 'perfect', begin to drift off axis.

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Hydrodynamic Penetration

Shaped Charges:
'Jet' Break Up & Particle Drift



Once the 'jet' has broken up, the individual particles will, unless the 'jet' is 'perfect', begin to drift off axis.

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Hydrodynamic Penetration

Shaped Charges:
'Jet' Break Up & Particle Drift



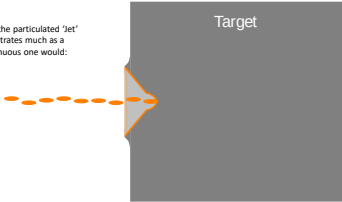
This means that the 'jet' will no longer penetrate as a single homogenous penetrator, but rather as a series of smaller projectiles.

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Hydrodynamic Penetration

Shaped Charges:
Penetration With Particle Drift

Initially the articulated 'jet' penetrates much as a continuous one would:



Target

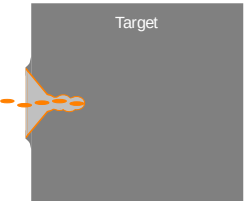


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Hydrodynamic Penetration

Shaped Charges:
Penetration With Particle Drift

However, the individual particles take distinctive "bites" out of the target, instead of creating a smooth penetration.

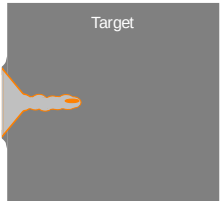


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Hydrodynamic Penetration

Shaped Charges:
Penetration With Particle Drift

The off axis particles are used up as they impact the wall of the existing penetration, instead of striking the base and increasing the depth of the hole.

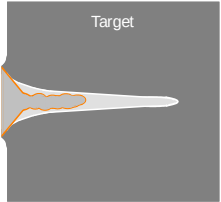


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Hydrodynamic Penetration

Shaped Charges:
Penetration With Particle Drift

Creating a shallow penetration when compared to a continuous, homogenous "jet".

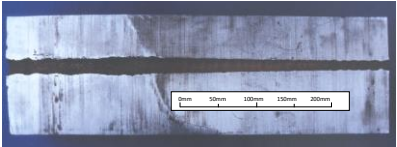


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Hydrodynamic Penetration

Shaped Charges:

What has created the 'bites' seen at the right and left of this picture?



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Hydrodynamic Penetration

Shaped Charges:

Basic Detonation Theory

Unimpeded an explosive detonation front will propagate in all directions at the same rate.

Therefore a detonation front travelling through an explosive charge will spread in a spherical pattern (Huyghens Principle) with the point of initiation at its epicentre.

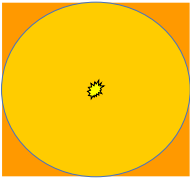


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Hydrodynamic Penetration

Shaped Charges:

Basic Detonation Theory



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Hydrodynamic Penetration

Shaped Charges:

Basic Detonation Theory

Here, we see the same effect from the side:



An extremely long explosive charge can be used to generate a detonation front that is (for all intents and purposes) flat: i.e. a "Plane Wave".

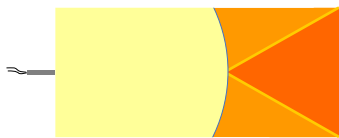


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Hydrodynamic Penetration

Shaped Charges:

Mass Reduction



As we know, a detonation front propagates in a spherical pattern with the point of initiation at its centre:



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Hydrodynamic Penetration

Shaped Charges:

Mass Reduction



The shape of the detonation wave as it comes into contact with and travels down the liner is important, but any explosive that does not contribute to this, is redundant and can be removed:

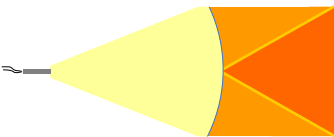


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Hydrodynamic Penetration

Shaped Charges:

Mass Reduction



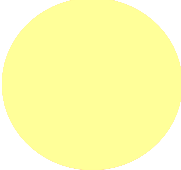
Forming a Shaped Charge in this fashion is referred to as 'Beehiving' or the charge itself may be called a 'Beehive', as it apparently looks like a beehive!

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Hydrodynamic Penetration

Shaped Charges:

Mass Reduction



The explosive mass can be reduced quite significantly, if we can simultaneously initiate the detonation wave around the edge of the charge:

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Hydrodynamic Penetration

Shaped Charges:

Mass Reduction



This is a sectioned view of the same effect.
Firstly a considerable amount of explosive can be removed:

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Hydrodynamic Penetration

Shaped Charges:

Peripheral Initiation



This can be achieved through 'Peripheral Initiation' which is a more efficient, but more technically demanding alternative means of reducing the charge mass than using 'Beehive' charges.

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Hydrodynamic Penetration

Shaped Charges:

Peripheral Initiation



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Hydrodynamic Penetration

Shaped Charges:

Peripheral Initiation



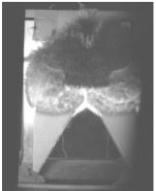
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Hydrodynamic Penetration

Shaped Charges:

Peripheral Initiation



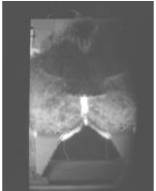
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Hydrodynamic Penetration

Shaped Charges:

Peripheral Initiation



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Hydrodynamic Penetration

Shaped Charges:

Liner Material

The most common material used as a Shaped Charge liner is Copper, as it fulfills the general requirements reasonably well.

The Ideal Properties for a Shaped Charge Liners are:

High Density

The target penetration achieved, is a function of the relationship between the densities of the liner and target materials (roughly a cubed root density rule).

This means that the denser the liner material the deeper it will penetrate into the target.

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Hydrodynamic Penetration

Shaped Charges:

Liner Material

The most common material used as a Shaped Charge liner is Copper, as it fulfills the general requirements reasonably well:

The Ideal Properties for a Shaped Charge Liners are:

High Ductility

The more ductile the material, the better it will stretch (without breaking up).

This will produce a longer thinner 'jet' which will penetrate more efficiently and from a greater 'Stand Off', which might be a useful advantage.



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Hydrodynamic Penetration

Shaped Charges:

Liner Material

The most common material used as a Shaped Charge liner is Copper, as it fulfills the general requirements reasonably well:

The Ideal Properties for a Shaped Charge Liners are:

High Sound Speed

The speed that sound (i.e. a shock wave) can travel through the liner material will limit the speed to which the liner material can be accelerated. Forcing the material to travel faster than this will result in 'jet' incoherence.



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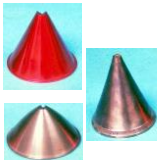
Hydrodynamic Penetration

Shaped Charges:

Alternative Liner Materials

Almost all materials, metallic and non-metallic, have properties that make them useful candidates for shaped charge liners, depending upon what you are aiming to achieve.

Material	Density	Ductility	Sound Speed	Notes
Copper	Medium	High	Medium	Relatively Cheap
Aluminium	V- Low	Medium	High	
Tungsten	High	Low	Medium	
Plastics	Low	V- High	Variable	
Zirconium	Low	High	Medium	Pyrophoric Material
Tantalum	High	High	Medium	Marginally Expensive
D-Uranium	High	High	Low	Radioactive Material!
Silver	Medium	High	Medium	Fairly Expensive
Gold	High	High	Low	Expensive
Platinum	High	High	Medium	Very Expensive



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Hydrodynamic Penetration

Shaped Charges:
Liner Shape

Changes in liner angle and shape will affect the formation of 'Jet'.



A copper liner with an internal angle of around 45 degrees, will produce a fast moving, long, thin and robust 'Jet'.



This will not particulate until it has travelled at least 3 charge diameters .

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Hydrodynamic Penetration

Shaped Charges:
Liner Shape



Where as, a copper liner with a narrower internal angle will produce a 'Jet' that is faster moving, thinner and more prone to particulation, even at short 'Stand Off' distances.

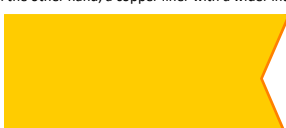


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Hydrodynamic Penetration

Shaped Charges:
Liner Shape

On the other hand, a copper liner with a wider internal angle will



produce a 'Jet' that is slower moving, fatter and unlikely to particulate even at large stand off distances.



This phenomenon can produce good results when the target is beyond the ideal 'Stand Off' of a conventional shaped charge.

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Hydrodynamic Penetration

Shaped Charges:
Liner Shape

Altering the shape of the liner to a shallow dish prevents the charge from 'jetting', rather it produces a smooth projectile travelling at around 1 – 5 km/s that do not stretch or deform even after flying considerable distances.



These are called Explosively Formed Projectiles (EFP's)

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Hydrodynamic Penetration

Explosively Formed Projectiles:

Sometimes referred to as a 'Misznay Schardin dishes'.



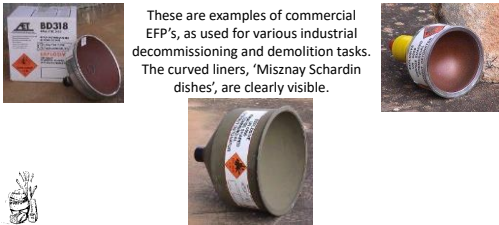
Charges containing such plates do not need to be as long as conventional shaped charges.

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Hydrodynamic Penetration

Explosively Formed Projectiles:

These are examples of commercial EFP's, as used for various industrial decommissioning and demolition tasks. The curved liners, 'Misznay Schardin dishes', are clearly visible.

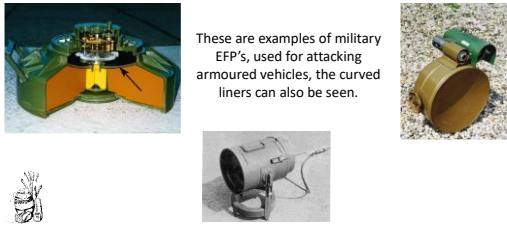


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Hydrodynamic Penetration

Explosively Formed Projectiles:

These are examples of military EFP's, used for attacking armoured vehicles, the curved liners can also be seen.



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Hydrodynamic Penetration

Explosively Formed Projectiles:

Detonation



As with conventional shaped charges, the detonation front travels down the charge towards the liner.

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Hydrodynamic Penetration

Explosively Formed Projectiles:

Detonation



But unlike conventional shaped charges a lower percentage of the liner material of an EFP is focused towards the central axis of the charge.

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Hydrodynamic Penetration

Explosively Formed Projectiles:
Detonation



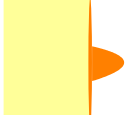
But unlike conventional shaped charges a lower percentage of the liner material of an EFP is focused towards the central axis of the charge.



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Hydrodynamic Penetration

Explosively Formed Projectiles:
Detonation



The liner is turned inside out by the detonation wave.

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Hydrodynamic Penetration

Explosively Formed Projectiles:

Formation & Flight



The detonation has imparted momentum to the liner, so as with conventional shaped charges, the liner material continues to flow even after all of the explosive has been consumed.



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Hydrodynamic Penetration

Explosively Formed Projectiles:
Formation & Flight





Since the liner material is moving at only half the speed of a conventional shaped charge jet and the front and rear portions are travelling at similar velocities, the projectile does not stretch like a conventional jet.

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Hydrodynamic Penetration

Explosively Formed Projectiles:
Formation & Flight





As such the projectile flows into a streamline shape and travels in this form until it strikes the target.

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Hydrodynamic Penetration

Explosively Formed Projectiles:
Formation & Flight





As such the projectile flows into a streamline shape and travels in this form until it strikes the target.

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Explosively Formed Projectiles:
Impact





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Any Questions?







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References

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References (continued)

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