A DARK SIDE OF THE FUEL CYCLE: SOME MILITARY USES OF DEPLETED URANIUM AND POTENTIAL CONSEQUENCES

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ABSTRACT

Over the past quarter century, depleted uranium (DU) has replaced tungsten alloys as the material of choice for penetrators in armour piercing rounds, in some armies, as well as a supplement to steel in tank armour. The tendency for adiabatic shear failure to overcome work hardening, and increased ductility are attributed for the improved ballistic performance. The aerosolization of a portion of the penetrator on impact creates a potential health hazard, particularly through ingesting resuspended aerosol particles. Bioassays of US and Canadian servicemen, potentially exposed to DU contamination, have failed to establish a link between DU and symptoms of "Gulf War illness". Further, Canadian testing has not been able to identify elevated levels of DU or even natural uranium in urine, hair or bone samples of veterans.

INTRODUCTION

In an effort to break the stalemate gripping the western front during World War 1 (WW 1), work was undertaken to develop vehicles, which could traverse the defensive trenchworks stretching from Switzerland to the North Sea. These trenches, protected by barbed wire and interlocking fire from machine guns, had become virtually unassailable to unprotected men on foot or horseback. The first deployment of such vehicles, using continuous "caterpillar-type" tracks and steel plate for protection, was at the Battle of the Somme in France on September 15, 1916. Here 32 Mark 1 "tanks", as shown in Fig. 1, took part in an attack and some of these were instrumental in the seizure of the village of Flers.[1] This began the inevitable seesaw between vehicle armour protection and armour-penetrating munitions designed to defeat these vehicles, that continues to this day.

This paper will examine the place of depleted uranium (DU) in the inventories of a number of modern armies and the threat it may pose to combatants and subsequently to peacekeepers and civilians. It will also touch on studies currently being conducted on Canadians who have potentially been exposed to DU.

HISTORICAL

The employment of armoured fighting vehicles in armed conflicts has an unbroken history since WW 1, with extensive armoured forces being deployed during and since WW 2. The political freeze of the Cold War following the truce in 1945 resulted in huge mechanized and armoured forces being deployed in Central Europe, by member nations of both the North Atlantic Treaty Organization (NATO) and the Warsaw Pact (WP). The most formidable vehicle fielded by both sides became the main battle tank (MBT), current versions of which now weigh some 60 t.[2] Much of this mass can be attributed to the protective armour, which until the late 1970s, was steel plate, known as rolled homogeneous armour (RHA). With the increasing effectiveness of anti-armour munitions, particularly the molten jets of shaped charge warheads, more exotic materials, such as ceramics, glass, composites and even explosive reactive armour (ERA) have been added to the steel shell. Fig. 2 shows an example of the frontal armour of a Russian T80U MBT.

During WW 2, the principal material for armour penetrators was also steel, used in full calibre warheads, with the intention that the striking energy of the projectile (some 10 MJ for the 88 mm gun on the German Tiger tanks) overmatch the target armour. The 88 mm is quoted as being able to defeat 234 mm of armour at 100 m.[3] This, however, results in the application of 1 644 MJ/m^2 to the target. As vehicle protective armour increased in thickness, subcalibre dense cores (initially tungsten carbide and later tungsten alloy) were used as penetrators, with light petals or sabots attached to the penetrators while the round was in the barrel. This allowed a larger surface area at the base of the round to permit the propelling gases to increase the muzzle velocity (and hence the muzzle energy) of the round at launch, while attacking a smaller area at the target. Thus, the 105 mm armour piercing discarding sabot (APDS) NATO round penetrator, similar to that shown in Fig. 4, had a muzzle velocity of 1475 m/s and again a muzzle energy of about 10 MJ. Now, however, the energy applied at the target was of the order of 7 800 MJ/m^2. These rounds achieved aerodynamic stability by spinning in flight and so were limited to a length/diameter (L/D) ratio of about 5:1. In order to increase the penetrator's terminal ballistics performance, smooth bore barrels were chosen to replace the rifled bores required to induce spin in the projectile prior to launch. Projectiles now achieved aerodynamic stability through having tail fins (Fig. 5) and are known as armour piercing fin stabilized discarding sabot (APFSDS) or, more simply, long rod penetrators. The major consequence of the design change, however, has been a dramatic increase in the L/D ratio, which for APFSDS was initially about 15:1, but has grown to 40:1 for experimental rounds.[4] The resulting energy applied to the target is 35 809 MJ/m^2 for the current US 120 mm DU penetrator.

PENETRATION MECHANICS

In order to understand the usage of DU as a penetrator material, a brief look at penetration mechanics is warranted. In the hyper velocity regime, for penetrator/target impacts in excess of 3 km/s, penetration is achieved by the mutual erosion of both the target and penetrator. Assuming that both the penetrator and target behave as

incompressible fluids, that penetration occurs at constant velocity and invoking conservation of momentum, it can be shown that:

$$P = L\sqrt{\frac{\rho_t}{\rho_p}} \qquad (1)$$

where P is depth of penetration in target
L is penetrator length
ρ_t is target density
ρ_p is penetrator density

It can be seen that the amount of penetration is dependent only on the length of the penetrator and the target and penetrator densities. As pressures at the penetrator/target interface are well in excess of the yield strengths of either material, material characteristics, such as strengths, are not significant. This type of analysis is valid for shaped charge jets and explosively formed penetrators,[5] as can be seen in Fig. 6, but not for the long rod penetrators discussed above. These latter, striking in the ordnance velocity range of 1500 – 1800 m/s, are better described by the semi-empirical Lanz-Odermatt equation:[6]

$$P = aL\sqrt{\frac{\rho_p}{\rho_t}}\, e^{-(2S/\rho_p v^2)} \qquad (2)$$

where a is a function of the penetrator length/diameter (L/D) ratio
S is a measure of target resistance, and
v is the impact velocity.

Both of the fitting parameters a and S are related to the mechanical properties of both the penetrator and target. It can be seen that, as the impact velocity, v, increases, penetration becomes independent of velocity, as described in Eqn (1).

For long rod penetrators, then, penetration can be increased by increasing the length, the density and the velocity. While current guns and propellants appear to be at the design limit for muzzle velocities, enhancements continue to the L/D ratio. As for density, the move from steel to tungsten penetrators increased the density from about 7 800 kg/m^3 to 17 500 kg/m^3. DU provides a further, albeit marginal increase to 18 500 kg/m^3, considering that penetration varies with the square root of the density.

As an aside, from the perspective of providing armour protection, it can be seen that increasing ρ_t will diminish penetration. Consequently, on the "heavy armor" (HA) version of the American Abrams M1A1 and M1A2 tanks, DU panels have been added to the turret frontal armour, as shown in Fig. 7.

Returning to the penetrators, the initial post war tungsten cores were tungsten carbide, but these were eventually replaced by tungsten alloyed with nickel, iron and

cobalt, sometimes known as tungsten heavy alloy (WHA). These latter have the hard but brittle tungsten particles embedded in a soft, ductile matrix, which serves to retard cracks and redistribute stresses. WHA penetrators are usually manufactured by sintering, with special attention required to ensure complete densification and preclude porosity resulting from entrapped gases or solidification shrinkage.

On impacting a RHA target, pressures at the penetrator/target interface approach 6 GPa. As seen in Fig. 8, the penetrator mushrooms within the target, with macroscopic plastic deformation followed by erosion. The initial strain is principally localized within the matrix, which rapidly work hardens to form the mushroom shape. A consequence of the mushrooming is that energy is expended radially to expand the penetration cavity.[7]

By comparison with tungsten, DU also has some processing challenges. It is sensitive to corrosion, trace element impurities, variations caused by heat treatment and hydrogen embrittlement and re-embrittlement. Also, finely divided DU particles are pyrophoric, so powder metallurgy is normally foregone in favour of casting and hot working (although special tooling is required). Also like tungsten, DU is alloyed, usually with 0.75 weight percent titanium.

Like WHA, DU alloy penetrators will mushroom on impact as the molten material is forced radially away from the penetrator. This plastic deformation results in an increase in the flow stress of the material due to work hardening and a competing decrease in flow stress due to thermal softening, with 90-95 % of the deformation energy appearing as heat, with temperatures of about 1800 °C being reached locally. In DU, unlike in WHA, the thermal softening overcomes the increase in flow stress, permitting adiabatic shearing to occur. This results in a "self-sharpening" of the penetrator, as the mushroom head is continually sheared from the penetrator body, as seen in Fig. 8. The net result is less energy expended in expanding the penetration cavity radially, with a concomitant increase in energy available for axial penetration.

Another penetration mechanism which has been proposed is the formation of a low melting temperature Fe-U eutectic at the penetrator tip, which assists in removing both target and erosion products from the penetration cavity.[7]

In general, then, against semi-infinite targets, DU penetrators can achieve penetrations of 10-15 % in excess of comparable WHA penetrators. Of even more significance, however, is the fact that DU rounds can achieve the same penetration as WHA rounds at significantly lower velocities, meaning that the DU round remains effective against any given target to significantly greater ranges (up to about 50 – 70 % greater).

Another particular advantage of DU over WHA is in its performance against oblique and/or spaced-plate targets. The greater ductility and toughness of DU penetrators seems to permit them to bend without fracturing, as opposed to the harder but more brittle WHA penetrators.

AVAILABILITY OF DU

Natural uranium is composed of three isotopes, ^{238}U, ^{235}U and ^{234}U. When processed for reactor fuel, particularly for light water reactors (PWRs and BWRs) the uranium is enriched in ^{235}U and ^{234}U, with the consequence that the tailings are depleted in these isotopes. Typical relative abundances and activities are provided in Table 1.

Table 1. Relative abundances and alpha activities of isotopes of natural and depleted uranium.[8]

Isotope	Relative Activity	Natural Uranium		Depleted Uranium	
		Mass (%)	Activity (%)	mass (%)	Activity (%)
^{238}U	1	99.2739	48.9	99.7990	85.5
^{235}U	6.33	0.7204	2.2	0.2001	1.1
^{234}U	17 400	0.0057	48.9	0.0009	13.4
Radioactivity (mBq/μg)		25.3		14.5	

It is interesting to note that DU, although slightly more dense than natural uranium, is about half as radioactive.

Reactor fuel, though, does not come only from the enrichment of natural uranium. It can also be reclaimed from spent fuel. In fact, over 107 000 t of uranium was recycled in the USA from 1952 to 1977. This would result in the probable inclusion of ^{239}Pu, ^{237}Np and ^{236}U in the enrichment tailings of DU, and thus in any penetrators fabricated from these tailings.

Another source of DU is tailings from uranium enriched for nuclear weapons. Current practice in the US is to only use DU from de-militarized or recycles rounds, as opposed to tailings from either reactor or weapons processing plants. Regardless the source, DU is essentially a waste byproduct of enrichment processes, and as such is inexpensive, especially compared to WHA. Combined with the fact that DU alloyed with 0.75 % Ti can be cast and rolled, rather than having to be sintered, the fabrication of DU penetrators is about the same cost as comparable WHA penetrators made in the US and less than half the cost of those made in Germany.

Coupled with the enhanced penetration characteristics, DU has become the long rod penetrator material of choice for a number of countries, including the United States, Great Britain, France and Russia. Correspondingly, DU is not used, as a matter of policy by a number of countries, including Germany, Switzerland and Canada.

AEROSOLIZATION OF DU

Uranium can exist in three solid forms as well as in the liquid and vapour phases. Table 2 below shows the transition points.

Table 2. Physical phases of uranium.

Temperature (°C)	Phase	
< 669	solid	α - orthorhombic
669- 776	solid	β - tetragonal
776 – 1132	solid	γ - body centred cubic
1132 – 4134	liquid	
> 4134	vapour	

As was already noted, impacts against hard targets result in local temperatures as high as 1800 °C, which results in a phase change to liquid. At these elevated temperatures, the uranium is readily oxidized, principally to U_3O_8 (75 %) and to UO_2 (25 %).[8] These oxides subsequently condense to solid aerosol particles. Oxidization is the source of the pyrophoric nature of DU impacts and is not present with WHA impacts. This effect enhances the effectiveness of DU penetrators, particularly inside the target.

Much work has been conducted in the US on determining the extent to which penetrators are converted to aerosols and on characterizing the aerosol particle size distributions. Against thick hard targets, it is estimated that some 18 % of the DU penetrator of 120 mm tank munitions is aerosolized, with virtually all these aerosols (91 – 96 %) having sizes < 10 μm, i.e., readily respirable. Of these respirable particles, roughly two thirds have dissolution half-times greater than 100 days, while the other third have half-times less than 10 days.[9] (Dissolution refers to the rate at which particles are dissolved in body – principally lung – fluids.) These particles would remain suspended in air for a significant period of time (hours to days), with most remaining in the target vehicles, but some available for escape to the atmosphere either through open hatches or remaining outside the target. A further hazard of resuspension of settled particles would exist to personnel engaged in either entering or inspecting contaminated vehicles. At any distance from contaminated vehicles, it is felt that aerosol concentrations would be diluted to safe levels.

HEALTH CONSEQUENCES OF DU CONTAMINATION

The human body's natural (aqueous) solutions act as solvents for any uranium with which they may come into contact. The principal oxides generated on aerosolization, UO_3, UO_2 and U_3O_8, all dissolve slowly. Once dissolved, uranium may react as a uranyl ion with biological molecules to produce cellular necrosis (cell death) and/or atrophy in the tubular walls in the kidneys, resulting in a diminished ability to filter impurities from the blood.

Once dissolved in blood, some 90 % of the uranium will be removed by the kidney and excreted in urine within 24-48 hrs of entering solution. The 10 % remaining in the blood can be deposited in bones, lungs, liver, kidney, fat and muscle. Inhaled insoluble uranium oxides can remain in the lungs for years, especially if they are < 2 μm and are thus more likely to be deposited in the alveoli. Gradually, these particles too, however, will also enter the bloodstream and eventually be excreted in urine.

Like other stable heavy metals, the principal biological hazard of uranium is felt to be toxicological, rather than radiological, with the organ at most risk being the kidney. The radiological hazard itself, via either external or internal pathways, is felt to be negligible. The worst exposures to US Army troops during the Gulf War were < 10 mSv, i.e., less than one fifth the former annual occupational dose limit and well below the level known to cause any health effects.

To date, very few (25 of 20 000) U.S. Army Gulf War veterans have been diagnosed with the types of kidney damage for which DU would be a possible causative agent. None of these individuals, however, was among the 33 veterans with the highest exposures to DU who are undergoing medical monitoring, while the diagnosis rates are consistent with rates for similar kidney problems among the general American population.[8]

MONITORING CANADIAN VETERANS

Canadian Forces (CF) personnel have been serving in areas where DU munitions have been expended, particularly in the Gulf, Kosovo and Bosnia. The principal danger from DU would be in the form of resuspended aerosols, which could have been ingested. Similar to servicemen from a number of countries, some Canadians have developed a variety of debilitating symptoms for which causes have yet to be attributed. Some see the significant difference from previous experiences, including other off-shore missions, as being the presence of DU in the environment. In an effort to establish or eliminate DU as a causative agent for these symptoms, euphemistically named "Gulf War illness", the CF, and militaries of other nations, have embarked upon a program of urinalysis of such veterans. The aim is to determine the extent of uranium in the urine and, where possible, to identify the isotopic ratios of any uranium isotopes present. This latter determination would indicate whether uranium contamination was due to DU, as distinct from natural uranium.

A number (103) of active and retired CF personnel participated in a uranium bioassay program, conducted in 2000. The total uranium concentration in 24 hr urine collections was analyzed by two separate laboratories for each of the personnel, with one lab using inductively coupled plasma mass spectroscopy (ICP-MS) and the other instrumental neutron activation analysis (INAA). The mean concentrations found were 4.5 ng/L and 17 ng/L, respectively. These values were consistent with quoted literature values of 4-6 ng/L, with an American study finding values ranging from 1-100 ng/L. The uranium concentration levels were too low in the urine to permit direct isotopic ratios to be determined, so hair assays were conducted with ratios of $^{238}U/^{235}U$ ranging from 120

to 145 +/- 20, (+/- 1 σ). By comparison, natural uranium has a ratio of 137.8 (Table 1) vs a ratio of 498.7 for DU. Finally, a single bone sample was analyzed from a deceased veteran, where the isotopic ratio was determined to be 138 +/- 4, again consistent with natural uranium.

It is felt that the ICP-MS results were more accurate than the INAA, considering the lower detection limit of 0.5 ng/L for the former and 40 ng/L for the latter. Further, the ICP-MS results are consistent with published data for non-occupationally exposed persons.[10]

CONCLUSIONS

DU penetrators exhibit superior terminal ballistic performance over WHA penetrators, principally due to their tendency towards adiabatic shear failure at the penetrator tip during penetration. They are also more effective against spaced, oblique and explosive reactive armour targets, due to their increased ductility. In short, they can either penetrate a greater target thickness under the same impact conditions, or penetrate the same target at a considerably greater range. A consequence of penetrator impact on hard targets, however, is the generation of aerosols, most of which are respirable and thus could result in the ingestion of DU into the body. To date, no direct linkage has been established between uranium contamination of the body due to DU munitions and "Gulf War illness" symptoms.

FUTURE WORK

In the US, it is felt that DU penetrator technology is at a mature stage and that there is little room for future exploitation. This, and the inherent distrust and environmental concerns among the general population, have led the US Army to try to develop tungsten alloys using innovative nanocrystals and tungsten "filaments" to mimic the performance of DU, although to date, none of these measures has been successful.[11]

In Canada, work continues to improve measurement capabilities for bioassay. A round robin comparison has been conducted among a number of university and private labs using blind synthetic urine (both blank and doped) samples, to be followed by real urine samples. Also, efforts are underway to investigate the appropriateness of including high resolution ICP-MS, or HR ICP-MS as a potential measuring instrument.

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FIGURES

Figure 1. One of the first WW 1 tanks, a British Mk 1, crossing a trench in France, 25 September, 1916.

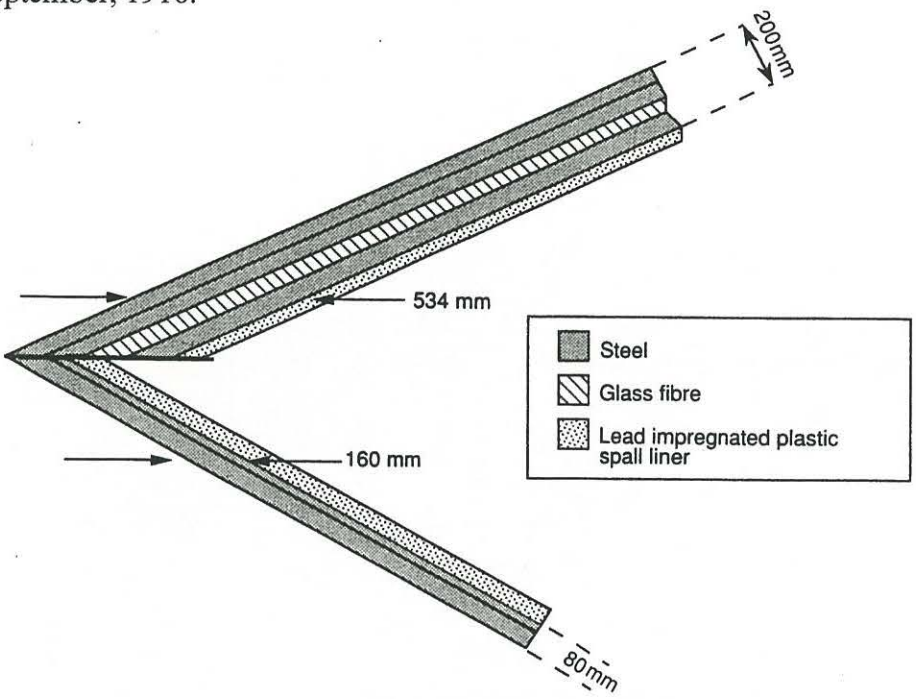


Figure 2. A representation of the frontal armour of a modern Russian main battle tank.

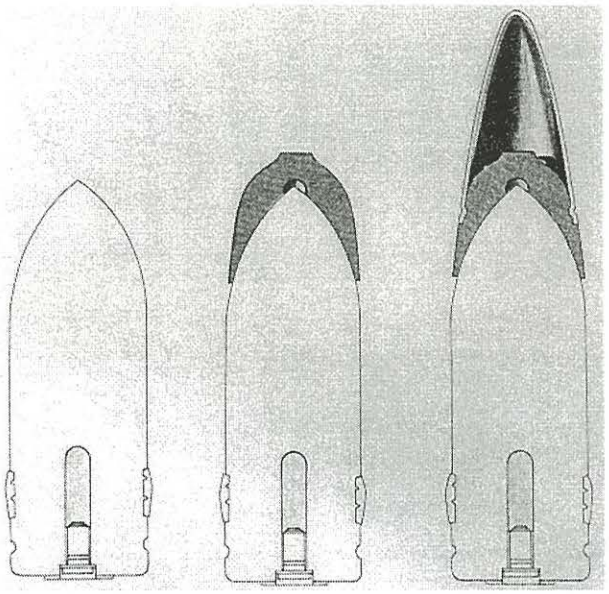


Figure 3. Examples of full calibre armour piercing shot, including, l to r, simple steel shot, a cap added to prevent shatter on impact (armour piercing capped or APC), and a further ballistic cap to reduce aerodynamic drag during flight (armour piercing capped ballistic capped or APCBC).

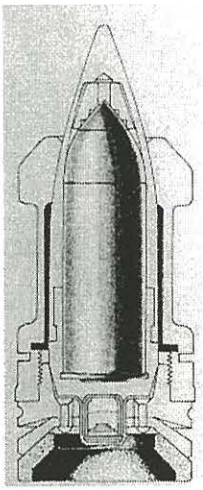


Figure 4. An example of an early armour piercing discarding sabot (APDS) round, with the tungsten core penetrator in the centre.

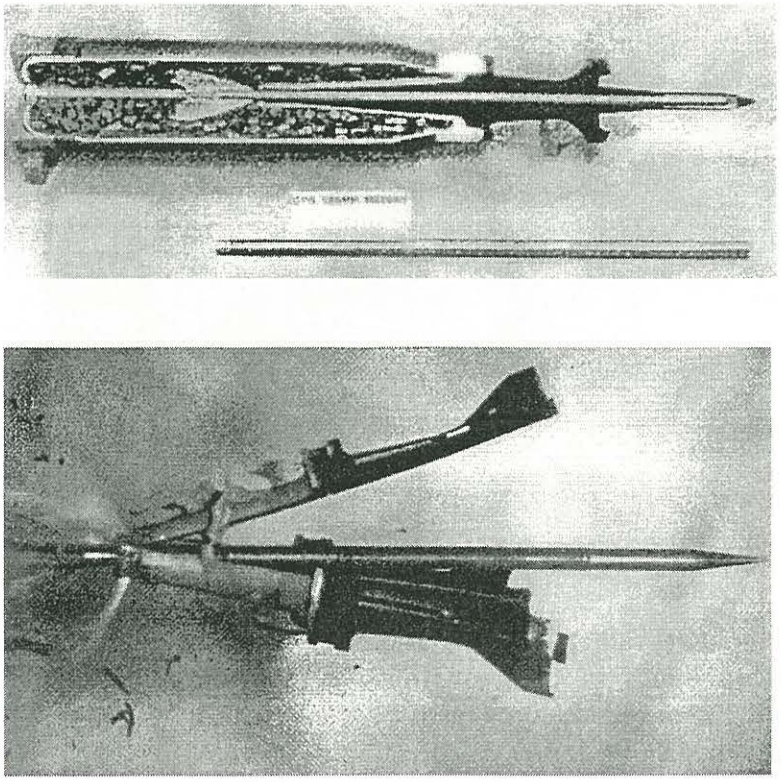


Figure 5. Two images of an armour piercing fin stabilized discarding sabot round. The first image shows the complete round with the DU penetrator beside it. The second shows the round after launch, with the sabots being discarded in flight.

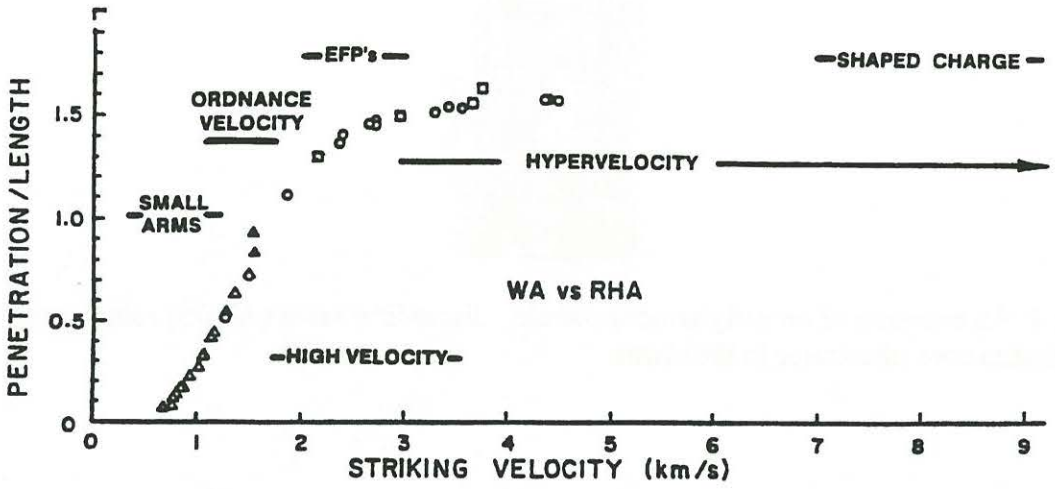


Figure 6. The ballistic "S" curve, showing the increase in penetration with increasing velocity in the ordnance range and the independence of penetration from velocity in the hypervelocity range.

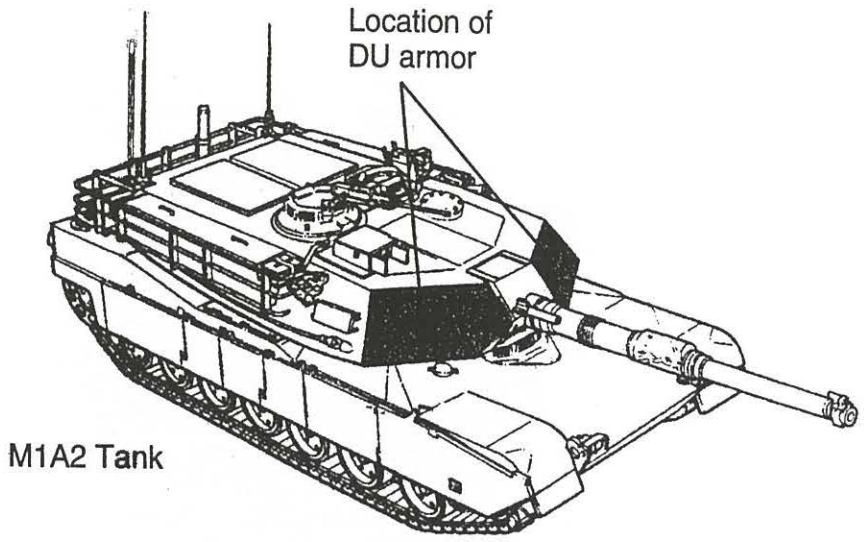
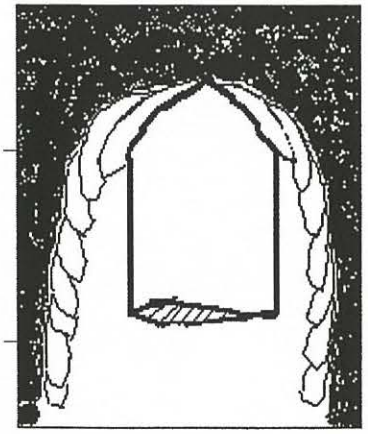
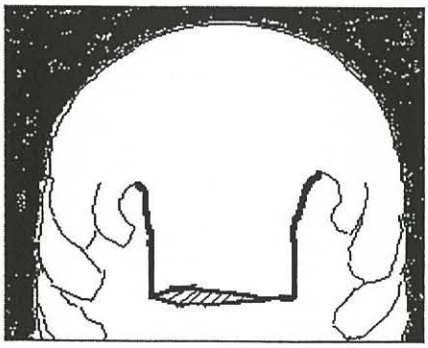


Figure 7. An American M1A2HA Abrams MBT showing the location of DU protective armour.



DU FORMS CHISEL NOSE DUE TO ITS ADIABATIC SHEAR PROPERTY AND PENETRATES TARGET WITH LESS ENERGY



TUNGSTEN FORMS MUSHROOM HEAD THAT DEGRADES PENETRATION

Figure 8. Diagram depicting two different penetration mechanisms, adiabatic shear failure in DU, resulting in "self sharpening", and work hardening causing mushrooming in WHA.