THE FUTURE OF WARHEADS, ARMOUR AND BALLISTICS

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Abstract

In 1983 a “Grand Old Man” of Ballistic Science, Dr. Robert J. Eichelberger, wrote[1]: ”Ballistic technology is generally considered a mature technology – as it should be after centuries of intensive attention of some of the finest scientific minds of the world.” He predicted that increased understanding of relevant physics and chemistry and development of mathematical techniques and computer models would be key elements in the future of ballistics and weapon system design. These predictions were very accurate!

But to-day’s developments and those of the foreseeable future go beyond this. Warheads and ballistics – interior, exterior and terminal – are very dependent on the use and properties of energetic materials – propellants and explosives – for their functioning. New, potentially very powerful substances such as the $N5^{+}$ and $N5^{-}$ ions and metallic hydrogen were created in labs. Air-breathing propulsion – ramjets etc. - and efficient use of the high combustion energy of some metals adds to the performance increase potential.

Increased use of intelligence, computers, sensors and fuzing in weapons, munitions and armours has added another dimension to the efficiency achievable. New high-performance materials have also meant great increases in effects and protection potential.

Developments possible in the next 20 years may have similar effect on warfare as the revolution in weapons, munitions and armour that occurred in the late 19th century. The statement that ”Ballistic technology is generally considered a mature technology” is no longer true. Any nation that will abstain from following the developments closely and exploiting their advances will run the risk both of having weapons, munitions and protection that prove inadequate and of making grave mis-investments.

INTRODUCTION

In 1983 Dr. Robert J. Eichelberger, past Director of the US Army Ballistic Research Laboratory, and an inventor of the shaped charge, wrote[1]: ”Ballistic technology is generally considered a mature technology – as it should be after centuries of intensive attention of some of the finest scientific minds of the world – da Vinci, Galilei, Euler, Laplace, Lagrange, von Neumann, von Karman, Urey, and many others. ...”. Eichelberger predicted that the increased understanding of relevant physics and chemistry and the development of mathematical techniques and computer models would be the key elements in the future of ballistics and weapon system design. His predictions were based on extensive feasibility studies and demonstrations performed in the 1970’s. We all know that his predictions were very accurate. However, to-day’s developments and those of the foreseeable future however go beyond what Eichelberger then believed was possible.

Most processes of warheads and ballistics – interior, exterior and terminal – are very dependent on the use and properties of energetic materials – propellants and explosives – for their functioning. In the latter part of the 19th century an extremely strong development took place in energetics, marked by the transition from black powder to nitrocellulose and multi-based propellants, and in warheads to high explosives, in all causing a revolutionary change in warfare, most apparent during WW I. During the 20th century - strangely enough, considering the occurrence of large wars in its first half - not so much happened in explosives (nuclear weapons disregarded) until the last two decades.

In other materials of importance there has also been an extremely strong development. Metals are one area where new manufacturing technologies have enabled production of extremely pure copper of high ductility and small grain size, resulting in great increase in the penetration of shaped charges. Other metals and metal composites, such as tantalum, uranium and sintered tungsten, have found important use in EFP and KE penetrators and other applications. Ceramics can much increase the protective ability of armour, and finally polymers and many types of composites have meant a revolution in the possibilities to produce high performance weapons, warheads and armours.

The increased use of intelligence, computers, sensors and fuzing in weapons and munitions has added another dimension to the efficiency achievable. There are, however, also many other requirements on weapons and munitions that must be simultaneously fulfilled, such as sensitivity, signature, (life-cycle) cost, handling, storage and environmental properties and finally those of destruction or recycling. This paper will examine the different areas of warheads, propulsion, ballistics and armour in the light of new developments and will give some examples of the increases in performance possible to expect.

TRENDS IN WEAPONS AND WARFARE

Armed forces in the West are becoming more and more adapted to International peace-keeping and also peace-enforcing operations of various sizes, either to intervene in local or regional conflicts, often under the auspices of the UN, the OSSE or the EU, or to participate in anti-terrorism activities. Low-level conflicts are also attracting more attention and require special means.

For weapons and munitions there are needs and requirements for

- increased performance
- long range, standoff capability
- short response time, high velocity
- high precision
- ability to penetrate outer defences
- low collateral effects
- high survivability under attack
- increased environmental compliance
- compatibility with network centric warfare concepts
- custom properties or performance tailored to the actual type of target.

In addition some new weapons and munitions types will become important in the future. These include electromagnetic weapons based on Laser, High Power Microwave (HPM) and Electromagnetic Pulse (EMP) technologies. Some of these may be applied directly from a platform-based weapon, for instance from an aircraft, an UAV, a ship or a vehicle, but also warheads having these effects can be designed, and can produce multiple types of effects, for instance concurrent HPM and fragmentation.

TRENDS IN PROTECTION

The new tasks of the armed forces of many countries create new and increased requirements on protection. The driving factor of a potential head-on confrontation between armoured forces in Central Europe is gone. But in low-level operations protection becomes extremely important again, since the troops will be exposed for long periods of time, with threats that may be unexpected, and own losses must always be kept at a minimum.

Ballistic protection deals with a few of the components, marked below by **bold** text, of the total protective system of a platform, consisting of protection against:

- intelligence
- detection
- localisation
- identification
- weapons attack
- **hit**
- **penetration** or **structural collapse**
- **behind-armour effects**
- **kill,** or **partial kill**
- verification of kill

Urgent needs and requirements exist for:

- Improved, physiologically acceptable armours for soldiers, policemen and others, effective against up to 5.56 mm and 7.62 mm AP projectiles.
- Increased protection for main battle tanks, also in other than frontal aspect; upgradeability
- Increased and situation-adaptable protection for lighter armoured vehicles, using appliqué armours and external protection, but also other components.
- Protection against top attack weapons
- Air portability for combat vehicles; for new MBTs very limited weight and size
- Mine protection, mainly for the vehicle crew and passengers.
- Improved protection of camps, check-points etc against direct and indirect fire

Increasing efforts are going into sensor-activated, close-in or remote protection against hit and penetration, using Reactive Armours and Defensive Aid Systems (DAS, APS, Active Armour) even for lighter vehicles, or anti-missile missiles. Many of these require new warhead and ballistic techniques to be applied – e.g. super-fast aiming.

TRENDS IN ENERGETIC MATERIALS

Late in the 19th century there was unprecedented development in weapons technologies, fuelled by the great improvements in propellants (double- and triple base "smokeless" propellant) and the advent of high explosives (picric acid, TNT), combined with highly industrialised, large-scale production methods[2]. At the time of WW I these innovations completely dominated and enabled much larger-scale operations, longer ranges and much greater destructive power, and they completely changed the picture of war.

In the 20th century there were many important technological developments leading to increased performance and lower sensitivity[2], such as CompB (RDX/TNT), PBXs (usually high RDX/HMX content, bound and stabilised by plastics) and IM (Insensitive Munitions) explosives. When it came to basic changes and new candidates there was, however, little progress until in the last two decades, when new high performance energetic substances such as CL-20, NTO, ADN and FOX-7 were synthetised and could be manufactured. Lately new interesting and potentially very powerful substances such as the N_5^+ and N_5^- ions and metallic hydrogen were created in laboratories. Also the use of air-breathing propulsion such as ram- and scramjets, and exploitation of the very high combustion energy of some metals has meant great increase potential in performance. Energetics can also be used for protection, such as in reactive armour and DAS (Defensive Aid Systems, also called Active Protection System – APS – or Active Armour).

The main reason why not much happened before was more a lack of understanding of energetic molecular structures than a poorly developed synthesis technique[3]. A great measure of conservatism among both military decision-makers and scientists has also hampered developments.

Today metallic hydrogen, with a relative "performance" of about 30 times that of HMX (see table 1 below) may be seen as the optimal ("chemical") energetic material[3]. This substance has yet to be produced in useful quantities and it is still much too early to determine whether it will ever be safe to handle[3] and possible to use.

The conservative image of explosives was that they would be conventional CHNO substances, with planar molecules containing carbon, hydrogen, nitrogen and oxygen. Many other types of energetic materials now exist, such as molecules/ions which are caged and often strained (CL-20, TEX, ONC, HNC, TTTO, N_x), have no carbon content (ADN), contain strained rings (TNAZ, N_5^-) and/or have high density functional groups (FOX-12, HHTDD)[3]. Closed ring structures also lead to greater crystalline density, an important attribute, which affects volumetric efficiency.

Table 1 Some computed properties of new (some not yet realised) HEDMs[3,4]

Compound	**Density** [g/cm^3]	**D** [km/s]	**P_{CJ}** [GPa]	**Rel. Energy** $V/V_0 = 2.2$ HMX=100)	**I_{sp}** [s]
HMX	1.89	9.3	39.3	$\boxed{100}$	266
CL-20	2.04	10.0	47.8	119	273
Boron Nitride/ HNO_3 *(Molecular Composite)*	2.20	18.0[1]	64	88	--
$N_5^+ N_5^-$	1.93-2.07	12.7	69	160	313
N_4 (T_d, tetrahedral)	2.3	15.5	122	310	424
N_8	2.7	19	206	498	--
N_{60}	1.97	12.3	65	161	331
TTTO	2.62	10.8	133	265	288
Poly-N	3.9	30	660	1058	516
Metal-H	0.8	--	--	~3000[2]	~1700

Notation: D = detonation velocity; P_{CJ} = detonation (Chapman-Jouguet) pressure; Rel. Energy at expansion 2.2, relevant for metal acceleration; I_{sp} = specific impulse, relevant for gun and rocket propulsion

1) Lower detonation velocities in different directions relative to the crystal planes
2) Only decomposition energy. Possible combustion of H_2 formed will add further energy and impulse

Quantum and molecular mechanics computations now offer means for estimating formation enthalpy. In combination with well established empirical techniques densities and detonation characteristics can be predicted with reasonable reliability. Comparisons between some existing and projected ("revolutionary") high energy explosives (HEDMs) are tabulated in table 1 above[3, 4].

In the last forty years it has become evident that nitrogen is the most important energetic ingredient in an explosive. It can chemically bond sufficient oxygen and/or fluorine for oxidizing a substantial part or all of the hydrogen and carbon elemental content with little consequence to the heat of formation; whereas similar bonding to carbon results in lowering heat of formation and potential energy, all other things equal. As important, the chemically bonded nitrogen in explosives is converted during detonation to entirely gaseous, bimolecular nitrogen, and as such contributes significantly to the detonation pressure. Oxygen (and/or fluorine) and carbon both come in second, where ratios of 1 to 2 appear to be optimal: whereas oxygen/fluorine balance is important in propellant chemistry it is not alone sufficient in explosive molecules.

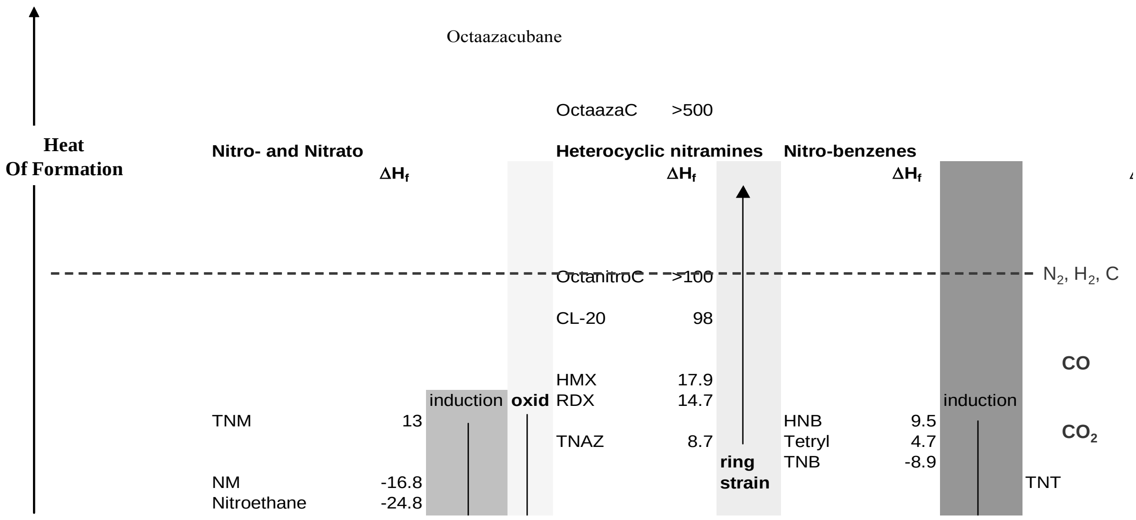


Figure 1 Effect of molecular factors on the enthalpy of formation of explosives.

The percentage of nitro-groups reaches a limit in hexanitrobenzene (HNB), which exhibits the greatest detonation energy of any aromatic. However its very unfavourable hygroscopic and light absorption characteristics are detrimental. Increasing interests are being directed towards incorporating nitrogen into heterocyclic aromatic structures.

Hydrogen is the least important elemental constituent, except for propellants where H_2 created will efficiently lower the average molecular weight of the gases.

The evolutionary development that occurred in the 1990s has made it possible to produce energetic materials enabling a 20-60 % increase in weapons systems performance in the near future. One obvious opportunity is also to use atmospheric oxygen to combust or detonate a high-energy fuel. Among the most energetic fuels are metals, such as boron, aluminium and magnesium, which can also be mixed with explosives acting as oxidizers, for instance ADN. Much more applied research will be needed to apply and tailor the new materials to various applications[3, 4].

Among the immediate opportunities of higher energy explosives is their inclusion in low-content formulations with stabilizing ingredients for meeting IM requirements while matching the performance of less stable explosive systems. Thus a device containing a 70 percent CL-20 explosive, with suitable stabilizing components, might match the performance of a high content RDX explosive system, ignoring cost. Similarly, one can project the initial application of explosives such as ONC and N_8 to augment, for instance, CL-20. Application of new technologies, such as nano-materials can also be used to lower sensitivity, increase performance and provide properties that can be tailored to the exact needs!

The challenge of creating molecules of increasing explosive potential, however, appears to be more difficult with each breakthrough, and as important - every new advancement is usually accompanied by many additional years of process development and qualification. The developmental process today, in fact, differs little from that experienced a century and a half ago, perhaps excepting times of war and of need for "quick fixes" when many obstacles can be circumvented.

INTERIOR BALLISTICS

Theoretical study of the interior ballistics of guns has been addressed by some of the most famous scientists and mathematicians throughout history (some names mentioned above), but it has been in the last half century that the greatest progress has been made in understanding the interior ballistic process as a highly coupled, transient event involving multiphase fluid dynamics, complex chemical kinetics, and mechanical response of propellants and aggregates of propellants.

Several decades ago, ignition-induced pressure waves in guns, sometimes leading to catastrophic results, motivated the transition from lumped-parameter representations (i.e., gas and solid phases of the propellant in the gun chamber treated as a well stirred mixture assumed to be characterized by a "space-mean" pressure at each instant in time) to transient, multiphase flow models involving ignition, flame-spread, and locally coupled interactions between propellant gas and solid grains (exchanges in mass, momentum, and energy). Advances in computational capabilities have made possible the development and routine use of one-, two-, and even three-dimensional multiphase flow interior ballistic codes, which along with the classical models provide a formidable array of tools for the modern interior ballistician to use as appropriate for gun propulsion charge design and diagnostic problems[5].

Future challenges rest not only in improving the representations for more detailed constitutive physics (e.g., multiphase ignition system sub-models, finite rate kinetics of propellant ignition and combustion, mechanical properties and fracture dynamics of solid propellants, mechanical and combustion characteristics of combustible cases and other parasitic components) and increasing the computational efficiency of particularly the multidimensional representations, but also in the formidable task of developing theoretical and experimental techniques for obtaining the required input to employ the vastly improved power of such codes in a meaningful and useful fashion. In concert with emerging experimental laboratory and range techniques, future multidimensional multiphase flow interior ballistics codes will empower gun propulsion researchers and charge designers to probe both the performance potential and associated risks of new gun propulsion concepts as never before.

In addition to conventional chemical solid propellant propulsion there are also new concepts such as regeneratively injected liquid propellants, ram accelerators (RAMAC/SCRAMAC)[6, 7, 8], light gas, electrothermal (ET) and electrothermal-chemical (ETC) propulsion. Electromagnetic (EM, MAG/Magnetic Accelerator Gun, railgun) propulsion is approaching practical application and has the potential to yield extreme lauch velocities. Double-base (NC-NCGL) and triple-base (NC-NG-NCGL) propellants may, in the long run, be replaced by new materials, such as FOX-12, with better performance, much better thermal stability and no need to add stabilising additives.

Typically for a gun-launched projectile 2/3 of the impulse will be consumed by accelerating the propellant gases. Hence one obvious way to increase performance will be to lower the molecular weight of the gases. In this context the optimum propellant should be metallic hydrogen, where propulsion will occur only by hydrogen gas! But there are also other possibilities to increase, for instance, the content of hydrogen in the gases, hence lowering their density. ET(C) may provide such possibilities.

Higher strength barrels, projectiles and better materials will mean that higher pressures can be used, ETC or liquid propulsion may make it possible to tailor and maintain the pressure for longer, and new propellants and additives may reduce temperature at higher performance, hence lowering gun tube wear. Principles such as fire-out-of-battery may reduce the weight of the weapon. Recoil is often the limiting factor in a gun design.

Combustible cartridge cases or caseless ammunition contribute to less munitions weight, higher charge energy and higher rates of fire. Some other innovations are Extruded, Impregnated charges (EI) and Programmed Splitting Stick propellants (PSS).

One obvious development trend is LOVA (LOw Vulnerability Ammunition) or IM propellants, that are less sensitive to heat or mechanical impact, and that will react less violently if accidentally ignited. They are typically designed as composite propellants with RDX or HMX as the oxidizer and a polymer as fuel and phlegmatising agent. Energetic polymers (see “Rocket propulsion”) and thermoplastic elastomers (TPE) add to the development opportunities!

Muzzle energies[9] for fielded medium and heavy gun systems might be possible to augment by up to 50 % in the longer term, seen from the side of chemistry of the powder. Velocities of 2000 m/s and above can be regularly attained for high-performance systems such as tank guns. High velocity gives longer range, better penetration in the target, and higher hit probabilities against moving targets. This may mean that, for instance, automatic anti-aircraft artillery (20-57 mm) might see a renaissance. The US Naval Surface Warfare Center, Dahlgren Div., Va. recently published[10] successful firing of a railgun, aiming at development of a weapon firing a projectile at up to 2350 m/s, yielding a range of over 300 km, for the the next Navy surface combatant (DDG-1000), an Integrated Power System (IPS) ship!

ROCKET PROPULSION

New oxidizers, like ADN or HNF, may replace AP as oxidizer for rocket solid propellant use. Energetic polymers, like GAP or Poly-NIMMO can serve to increase the specific impulse of composite propellants.

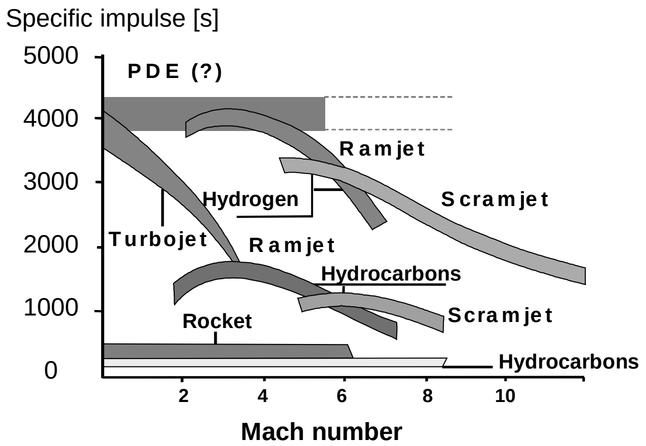


Figure 2 Specific impulse for different propulsion engines

An obvious way to increase propulsion performance will be to utilise atmospheric oxygen and let the propulsion device only contain the fuel. Some such devices are ramjets, scramjets and pulse detonation engines (PDE)[11,12] (and of course also the more complex turbo-jets). A special, simple device is the solid fuel ramjet (SOFRAM, fig. 3)[13]. Use of atmospheric oxygen will enable about a <u>five-fold increase</u> in range performance per mass unit of fuel, compared with a traditional rocket.

A drawback of all these engines, except the PDE which can operate from zero speed, is that they require high initial velocity in order to function. Ways to solve this include gun or rocket launch. A SOFRAM engine may be designed to provide both the initial propulsion (as a rocket) and the sustained, air-breathing one. From the diagram, rockets may appear inefficient; however, they give the highest thrust per mass unit of all the propulsion engines.

Further problems are design, manufacture, precision, strength and other material properties of the propellant, the combustion chamber and its Laval nozzle (the PDE essentially needs no nozzle).

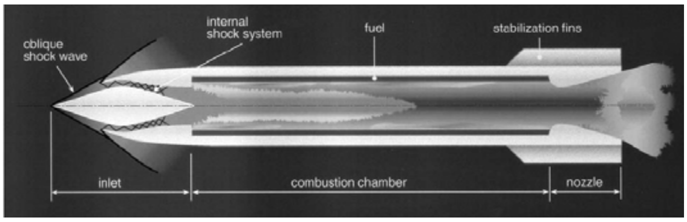
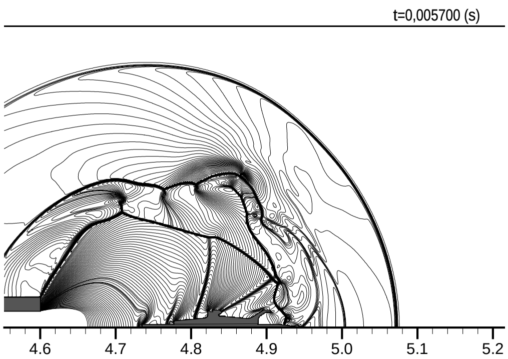


Figure 3 Solid fuel ramjet (SOFRAM), courtesy TNO[13]

Modern computational fluid dynamics has meant similar advantages for modelling combustion in propulsion engines as for gun interior ballistics. Future advances will be essential to overcome the problems of modelling solid propellant and air-breathing propulsion devices. Important problems to solve are reactive flows, turbulence, shock waves and their interaction with the flow.

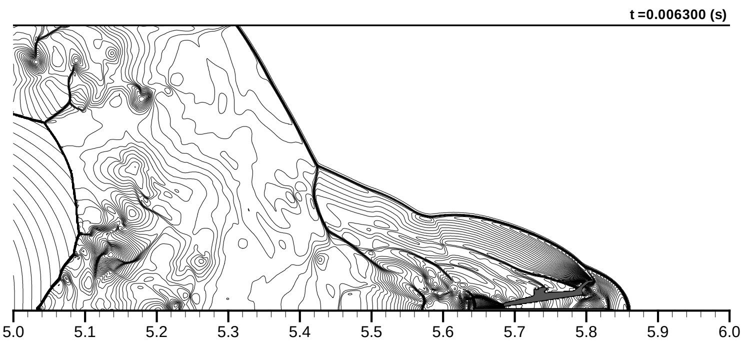
LAUNCH DYNAMICS



Improved control of gun dynamics can lead to improved precision. The US so-called ”Smart Barrel” concept is aimed at dramatically increasing the stability of the barrel at launch, hence increasing precision of the projectile.

Launch Dynamics, also known as Intermediate Ballistics can be divided into four main areas :

- Muzzle artifices (muzzle brakes, etc.),
- Sabot discard,
- Weapon system environment (blast, overpressure, etc.)
- Determination of muzzle conditions (initial projectile launch conditions, etc.)



Figures 4a, 4b Intermediate ballistics computations, 2-D unsteady CFD of the separation process of a saboted long rod projectile[14]

The first three topics relate to Fluid Dynamics, the last one concerns System Dynamics.

Coupling 1-D or 2-D interior ballistic codes with 3-D hydrodynamic codes now enables prediction of dynamic behaviour of projectile and gun barrel during the interior propulsion phase. By doing this the relaxation of the interior ballistic constraints of the sabot components can be deduced, expressing them in the form of initial discard conditions (example: lateral and angular velocities of sabot components).

The numerically unsteady prediction of sabot discard in intermediate ballistic flow conditions is still a challenge, but strong progress in CFD computations has enabled solutions to this kind of problem. For example, the 2-D or 3-D intermediate ballistic flow can be considered as two calorically perfect non-mixing gases (bi-phase propellant gas and air) separated by a moving contact surface discontinuity. The precursor flow, the main propellant gas flow, the main structures of the unsteady over-expanded jet flow (Mach disk, barrel shock, vortex ring and blast wave), and the projectile and sabot aerodynamics, can be numerically well captured (see Figs. 4a, 4b).

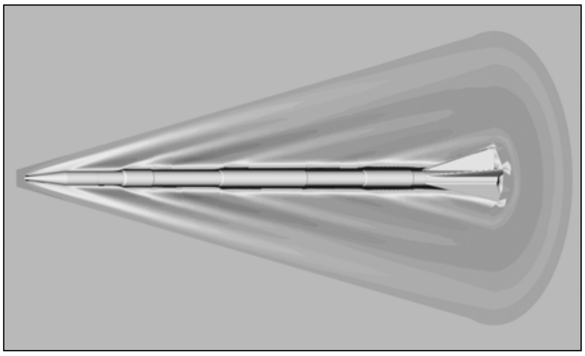


Figure 5 APFSDS Mach number field, URANS computations, Mach 4.5[17]

EXTERIOR BALLISTICS

Some trends in exterior ballistics are use of sub-calibre, optimal aerodynamic bodies for increased range, pioneered by the late Dr. Gerald Bull and the Space Research Corporation; base-bleed, invented by FOA, which can augment range by 40 % while maintaining or lowering scatter; and extended range solutions based on fly-out or SOFRAM propulsion, which may triple range or more. SOFRAM can be designed to control and improve precision, however it is anticipated that most future projectiles for anti-tank and artillery will have some degree of intelligence and guidance.

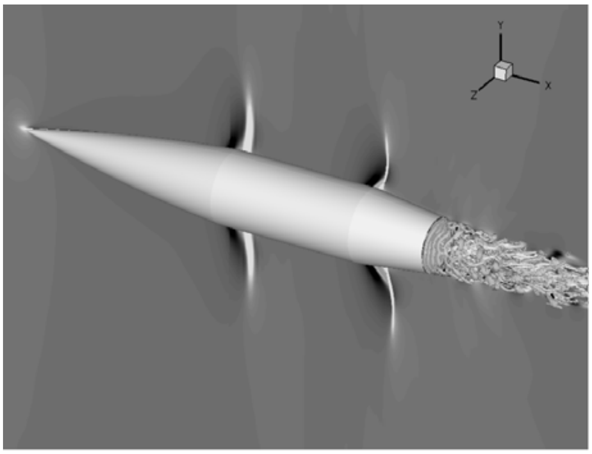


Figure 6 Spinning projectile with boattail, ZDES computations, Mach 0.91, $-\alpha = 2°$, pseudo-schlieren visualization, iso-contours of Q iterion[16]

Computational Fluid Dynamics has been successfully used for many years to determine the static aerodynamic coefficients of projectiles and missiles[15]. Progress in CFD now allows unsteady aerodynamics prediction, often with an accuracy of down to ± 5 %. For example the Magnus effect (C_y & C_n) and the roll and pitch damping moment (C_{lp} & C_{mq}) coefficients can be predicted. Computations, based on 3-D Navier-Stokes equations (RANS, URANS) appear to be well suited (see figure 5)[17]. However, a main remaining difficulty is the Magnus prediction of spinning projectiles in subsonic and transonic regimes. Under separated flow conditions, RANS methodology is inappropriate. Unsteadiness of the recirculating flow might be responsible for the failure of these turbulence models to properly match both the evolution and the magnitude of the base flow area. Advanced computational hybrid methods like Large Eddy Simulations (LES) or Zonal Detached Eddy Simulation (ZDES, fig. 6)[16] seem to be promising for the description of the physics of the flow (boat-tail region, near-wake, time averaged flowfield, etc.).

The stability of high L/D projectiles is confronted with detrimental aeroelasticity effects induced by the coupling between the natural bending of the material (depending on the body rigidity) and the aerodynamics motions (yaw, pitch, roll). A numerical approach based on Lagrangian formulation coupled with CFD[17], has enabled the motion and bending of a supersonic very high L/D projectile to be correctly formulated. Using this model the influence of the key parameters, such as the roll rate, on the projectile's dynamic behaviour can be accurately predicted.

There is a general trend towards terminally guided systems, also for artillery, especially for extended range capabilities. For fly-out solutions navigation and terminal guidance are essential. Limited terminal corrections can be achieved by aerodynamic means, such as small steerable ailerons or fins, or by small, suitably placed and controllable thrusters/rockets, fixed impulse rockets or propellant or high explosive acceleration of counter-masses. Correction of spinning projectiles is also possible. Even with rather simple correction systems building on one of these principles, and with proper sensors and on-board intelligence, hits in moving targets can be possible.

WARHEAD MECHANICS

More powerful explosives do not by themselves lead to an advance in high performance warheads. Developmental immaturity and stringent IM requirements may be severe obstacles to their use.

Wave-shaping and initiation are important means for improving warhead performance, and will make it possible to decrease the length of an explosive warhead and to increase coupling efficiency between explosive and metal liners. Adaptive initiation and/or wave-shaping exploits the technologies available for target sensing, recognition, and guidance, permitting fuzing and function to be dynamically modified just prior to weapons impact in a manner to inflict optimal energy delivery to the target.

Some of these innovations depend on developing transient detonation convergence and mach wave formation in the warhead. Recent efforts are addressing means for sustaining convergence in order to further reduce warhead size and to add another degree of freedom in the design of fragmentation, EFP and shaped charge devices. These approaches can lead to substantial increases in the velocities and pressures achieved by current explosives by use of so-called overdriven detonations.

Confirming results can be found from 1965 and forward[18, 19, 20] describing coaxial charges composed of solid explosives, where C-J pressures were measured in the core of a cylindrical plastic-bonded explosive, with an outer H E sleeve containing high concentrations of tungsten, thus reaching a high density and consequently a higher detonation velocity. Peak pressures as high as 2.3 times the normal C-J were reported. Thus a faster detonating sleeve explosive is required to initiate the core. Such a coaxial combination will obviously be limited by the detonation velocity ratio between sleeve and core. More sophisticated solutions, using programmed initiation, can overcome this limitation.

An explanation in terms of ideal detonation theory is offered in Figure 7. The von Neumann spike condition is denoted P_1, and the C-J state is CJ_1 in a steady-state divergent detonation front. The Rayleigh line connecting P-v coordinates at ambient, C-J and the spike condition define the detonation velocity. The explosive core enveloped within a convergent front is compressed to a “spike” pressure greater than P_1. In fact this occurs normally when, for example, a booster of higher detonation pressure is used to initiate a main charge or as a result of non-sustainable ring (peripheral) initiation. In these latter scenarios, detonation conditions relax back to the normal steady state “1” condition. If convergence is sustained, a new C-J state CJ_2 will develop and persist over the duration of the convergent condition. Furthermore it is likely that the chemistry differs at the

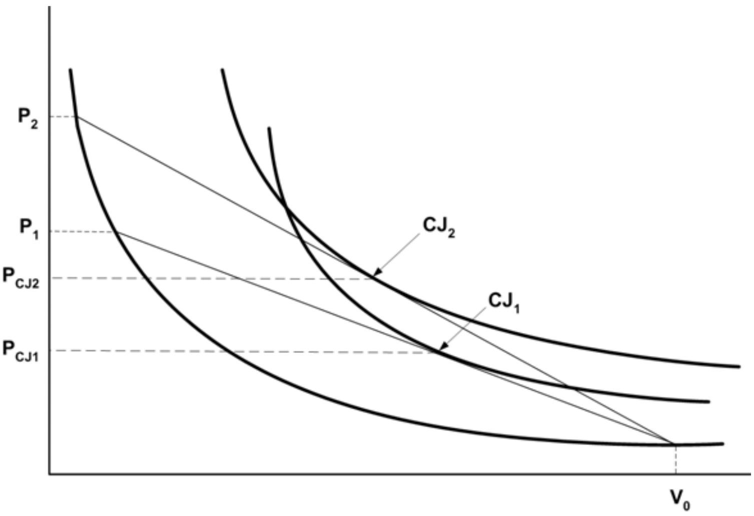


Figure 7 Differences in detonation product isentropes and C-J conditions resulting from divergent and convergent detonation

higher pressure as it must also vary with time for non-sustainable overpressure conditions that result from flyer plate impact or a high pressure boosted initiation.

The new states for the onset of convergent detonation between the elevated von Neumann spike and the C-J states are denoted by the subscript "2". In this case the steady-state condition is driven by the sustained supra-pressure along the convergent front.

The faster detonation velocity is reflected by a Rayleigh line of increased negative slope. This line must connect with a tangency point at a uniquely different reaction product isentrope, reflecting correspondingly different product chemistry.

At these elevated detonation conditions one should realize substantial increases in overpressure blast, metal plate acceleration and shaped charge jetting.

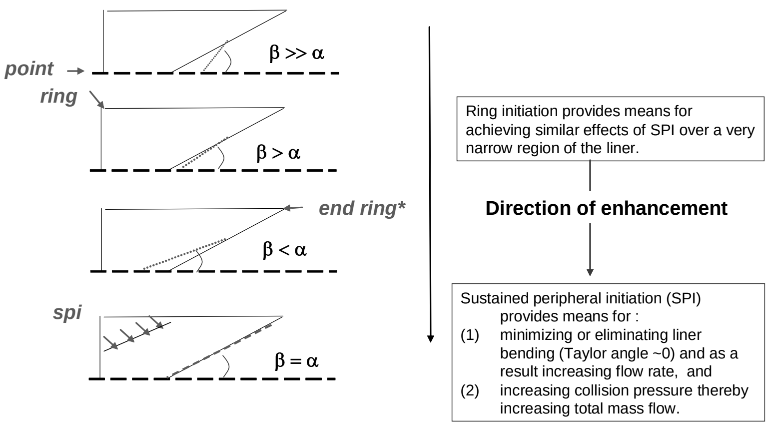


Figure 8 Sustained peripheral initiation offers a possibility of equalling and exceeding projected performance levels of shaped charges by combining envisioned high energy futuristic explosives with today's lower energy explosives[21].

For high performance munitions such as missile fragmentation ones and shaped charges the improvements in high explosives (CL-20, HEDM) means an increased development potential and new possibilities that may be realised even if only small amounts of new HEDMs will be used. Control of charge precision, initiation, explosive and liner material quality and improved manufacturing methods will combine to enable much increased penetration. Heavy liner materials such as tantalum, uranium and tungsten alloy will contribute. Penetration in RHA of HEAT (shaped charge) warheads for qualified missile applications might be possible to increase by up to 50 % in the medium term; however the implications of complex high precision shaped charge designs and their performance against new armour protection effects must also be considered. If qualified HEDMs like N_x can be used in the more distant future, anti-tank warheads will be likely to need a total re-design, and much both basic and applied research will be necessary. One reason is that dynamic material properties in these regimes are largely unknown, and materials may indeed behave totally differently when exposed to pressures exceeding 100 GPa (1 Mbar), another is the much higher detonation velocities attainable, whereas for many materials concerned the sonic velocity may not increase much with pressure.

Shaped charge jets will continue to be sensitive to interference from reactive armours, layered armour structures and high strength armour materials such as ceramics. Tandem or triplex shaped charges/EFPs and other solutions will make it possible to combat these protective methods and may eventually <u>give frontal attitude penetration capability to a man-portable AT system</u>.

EFPs have a great potential future in stand-off warheads, such as side-action mines or top-action missile warheads against armoured vehicles and other qualified targets. Heavy liner materials, such as tantalum, uranium and tungsten alloy increase range and efficiency. Combining EFPs with reactive liner materials can enable much increased behind-armour effects.

For deep penetration (anti-bunker) warheads improved low sensitivity explosives are needed.

For air-bursting or underwater warheads there is much improvement possible by using the surrounding ambience for an oxidiser, and an <u>increase of the available energy by a factor of about 5</u> relative to TNT is possible, even in the short term, by using highly energetic fuels such as boron or aluminium. Examples are so-called thermobaric warheads, which are based on a mixture containing a powdered metallic fuel which is combusted with atmospheric oxygen, and which give a very high blast impulse. Similar energetic materials can also be applied underwater or in materials containing (crystal) water, such as concrete.

Warheads that adapt their effect pattern to the current target – multi-purpose warheads - will become common. This may mean that, for instance, most fragments will be propelled towards the target in order to increase the spatial density of fragments that will hit, or warheads that can alternate between any of shaped and cutting charge, EFP, fragmentation and/or blast effect, depending on the kind of target affected. Such warheads will need intelligence and mostly also built-in sensors to function.

Another way of adaptation is to have graded or scaleable effects, such as having effect alternatives with different properties in order to avoid collateral damage and risk to civilians or own troops, depending on the situation. The simplest example is a munition that provides alternative functions, for example with and without fragmentation. More sophisticated alternatives will be possible, even such ones that can alternate between lethal and less lethal effects.

A scaleable effects weapon, has, in contrast to multipurpose munitions or warheads, a “sliding” control rather than a “switch”. One example is a variable yield blast/fragmentation warhead in which a controllable portion of the explosive content will detonate, using insensitive and environmentally friendly energetic materials to avoid collateral damage by unexploded material.

Such graded and scaleable effect munitions will increase the options and possibilities to intervene for the military commander, and will facilitate logistics. The effects can be selected before loading, in the weapon before firing, in the trajectory by remote control, or by an intelligent target sensing system just before impact. To have alternative munitions would not usually be favoured for the simpler and less advanced weapon systems, especially not for ones that are carried. A small calibre munition that could fulfil normal requirements when used at distance and against harder targets such as cars, while being adaptable to become a less lethal munition, even at short range, would be highly desirable. One (scaleable) possibility could be an assault rifle enabling a variable muzzle velocity while using common bullets (e.g. with a by-pass valve for gases).

Proper non-lethal systems are less of a military requirement than one for police and para-military forces operating in an essentially non-combat environment. However, in International environments military units often operate with “policing” tasks. A large multitude of possibilities exist. For many of these it will be preferable that they can be used in the normal weapons of the troops.

To counteract future enemy active trajectory measuring protection systems, munitions may be developed which have an unpredictable trajectory and/or an unpredictable timing. This may be achieved by steerable munitions, possibly combined with rocket-assisted acceleration during the final phase.

Insensitive Munitions (IM) remain important, for warheads as well as for propulsion charges. Especially in International operations, where troops will operate with weapons loaded and vehicles full of munitions, where distance to own troops and civilian population may be short, and where the requirement of force protection is high, IM munitions will be essential. Increased life-cycle endurance, and improved monitoring of munitions to assure when they have to end their service life will also be very important.

TERMINAL BALLISTICS, ARMOUR AND PERSONAL PROTECTION

For body armour, the demands for low weight, high weight protection efficiency, adaptability to different threats and comfort for the soldier are high. The latter becomes even more important in hot climates where the heat load can become excessive. Personal protection consists of body armour i. e. helmet and vest. Earlier types of body armour were designed mainly to protect against fragments from artillery shells. In international operations, though, the main threat comes from small calibre weapons with very varying penetration capabilities. Most of these threats demand very weight-efficient armours using modern polymer fabrics and special reinforcement plates in order not to violate mobility too much. For the severest threats, vests protecting only a smaller part of the body might be considered. International operations often involve clearing missions demanding special types of personal protection covering the whole body, including special boots. In this case, one has to accept very limited mobility.

Important systems requirements for qualified land platform armour are:

- Increased weight efficiency of the basic armour
- Modularity – components possible to upgrade when facing new threats
- 360º protection
- Top attack protection
- Mine protection – for blast and penetrating mines

From technical aspect this means:

- New materials – ceramics, nano-materials, improved metals, polymeric fibres
- Higher strength materials
- Adaptive (electrically controllable) properties
- Self healing, or even self repairing materials
- Smart geometries – spaced armour, oblique armour, inhomogeneous armour
- Intelligent, with integrated sensors
- Exterior protection – bar armour
- Reactive armours
- Stand-off protection - Defensive Aid Systems (DAS, Active Protection System – APS – or Active Armour)
- Electric and electromagnetic armours
- High energy laser defences
- Special anti-missile missiles

One of the most important aspects of current and future armour development is the improvement of the materials which are the basic constituents of armour systems. Improved materials and their combinations are indispensable to achieve armour systems which are affordable and resilient, besides being lightweight. Fig. 9 gives an overview of materials relevant to armour.

Examples of important on-going material developments are:

- Transparent ceramic armour, possibly particulated (pellets) and/or laminated with transparent polymer backing;

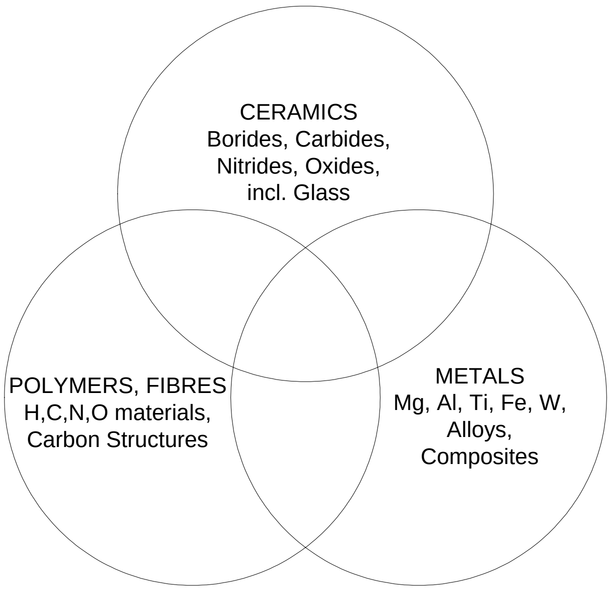


Figure 9 Material development for armours

- Metal Matrix Composites (MMC’s) that combine toughness and hardness,
- Amorphous metal alloys which combine high strength with polymer-like behaviour, enabling great energy absorption;
- Liquid armour with electrically controllable rheological properties, enabling repositioning of part of the armour within seconds to a certain part of the vehicle or to use as a close-in hard-kill active protection measure (jet) through high-pressure pumps, nozzles or explosive propulsion.
- Body armour using high-strength fibre fabrics combined with shear thickening fluids or -solids to combine comfort with high protection levels; the fibres may be special auxetic fibres (with negative Poisson’s ratio) to avoid fibre pull-out from the matrix.

Besides material development armour systems are improved by combining existing materials and components. Examples are:

- Upgrading of spaced metal armour to electromagnetic reactive armour (against shaped charge jets) by filling the spaces with capacitor banks;
- Using the impact energy of the threat to prolong encapsulation of ceramics to facilitate “dwell” or “interface defeat”;
- Combining sensors and explosive reactive armour (ERA) into a multifunctional armour system in which the flyer-plates of the ERA can be deliberately triggered and used as a hard-kill active protection measure.

The only feasible way to keep protection, mobility and firepower of an armoured vehicle balanced without excessive weight increase will be the application of an effective active protection system (APS) using hard-kill measures.

The very optimistic requirements, especially by the US DoD, of future manned 20-ton, air transportable fighting vehicles (FCS) with capabilities very close to those of present 60-ton-plus MBTs will be likely to yield to more realistic concepts of manned 40-ton fighting vehicles. Modern combat scenarios include ambushes, in which vehicles are being hit by mines (including remote side action mines), RPG-7-like weapons (or worse) and KE penetrators (typically up to and including 14.5 mm). This type of threat scenario may force high protection levels to cover not only the personnel compartment (possibly as a “citadel”) but also the engine and transmission compartment.

Even if a high performance Active Protective System (APS) will be available it will remain an absolute necessity to achieve - within the weight limits of the vehicle - the highest possible passive (possibly reactive) armour protection level in order to:

- Avoid a “cheap kill” (“old threats never die”!)
- Protect against all threats (bullets, AP KE projectiles, blast and fragments);

- Offer a certain level of protection in case of saturation of the APS;
- Protect against residual threats after successful engagement of the APS;
- Reduce consequences of an overmatch threat (heavier than specified);
- Offer a certain level of protection if APS is disturbed by enemy;
- Offer a certain level of protection against threats unaffected by APS;
- Offer a certain level of protection if APS cannot be switched on or is not effective.

The most promising potential of the new materials can be found in ceramics where, especially against KE-penetrators, spectacular results can be obtained. The inherent very high compressive strength of ceramics is very poorly exploited in present armour systems[22]. If tensile stresses can be avoided crack formation can be suppressed and the protective ability can increase much, as was demonstrated in experiments [22, 23] using highly compressed and confined material. This resulted in what has been termed "interface defeat" or "dwell", i. e. that even a high density (tungsten), long rod penetrator at high velocity ($\leq$ 2000 m/s) achieves no penetration at all[22]. If such armour systems can be realised their weight efficiency could be dramatically increased.

Another way of obtaining spectacular weight-efficiencies is to use dynamic (moving) armour components like in reactive armour systems and APSs. Most of these systems rely on chemical energetic components and their first generation was optimised against shaped charge (HEAT) warheads from recoilless weapons or missiles. A dynamic armour system requires launching a substantial amount of material and energy in the path of an approaching warhead. This can also be achieved by electromagnetic or gun acceleration of the protective components. The requirements of short response times, exact timing, velocity and accuracy are high for such systems. An APS can also be tailored to counteract top-attack weapons.

Apart from "conventional" mechanical hard-kill means to defeat the threat, electromagnetic power can be used. Electric armour, e.g. destroying the penetrator by short-circuiting a strong electric current through it, has already been demonstrated as being highly effective against shaped charge jets[24] and as energy-storage and pulsed power devices improve, it may become a viable means of protection also against KE-penetrators. In a longer time perspective, high-power lasers may be used, especially against relatively soft-skinned targets such as missiles, radically simplifying the problem of hitting fast-moving threats.

Camps and other more permanent and static installations will be protected by using better fortification materials and techniques, such as pre-fabricated elements and casting of high performance concrete (HPC) with bar, net or fibre reinforcement. Measures to keep any threats at distance, such as barriers, fences, ponds or moats, or stretches of dense forest, will help protect against car bombs and similar, supplemented by proper gates, sluices, security and inspection procedures to halt and screen approaching vehicles and persons. Long range weapons must be considered by ensuring that hostile parties are not allowed to deploy artillery, mortars etc close enough and by using air-defence systems appropriate for the anticipated threat.

In many situations during out-of-area missions there is great need for rapidly erectable and transportable field fortifications. These can be used as fighting positions, bunkers and command or observation posts. Such fortifications will be set up temporarily where they are needed and can be moved and rebuilt relatively fast at new locations. They can be upgraded using low cost on-site geological materials and have the potential of becoming fairly comfortable also during longer sojourns.

GUIDANCE, FUZING AND IGNITION SYSTEMS

The development of digital computer processors has, since long, followed the so-called Moore's Law, which predicts a doubling of performance per 18 months. However, in order to permit this strong development to continue beyond about 2010 a transition from the present semiconductor technology to a new one must occur.

The trends for sensors go in the direction of increased resolution for individual sensors, integration of different types of sensors in multi-sensor systems, and use of advanced signal processing, data and information fusion. There is focus on passive and, hence, less detectable sensors.

Advanced processing in software controlled digital processors will successively replace most specialised hardware and the trends in miniaturisation will continue, enabling more and more intelligence to be fitted in the limited space of weapons and munitions. Great advances in database and storage technology will enable massive amounts of data, such as terrain information or imaging, to be brought, and large amounts of new data to be collected, processed, organised, compared and analysed in an on-board system. Also advances in data link technology will mean that secure operator control can, if desired (which will often be the case in International operations), be maintained during the entire flight sequence. In the future it is believed that almost all weapons and munitions systems will possess some degree of intelligence. This will mean increased capabilities and discrimination, and increased resistance to camouflage and electronic warfare interference for target locators, terminal guidance systems and fuzing systems. Simple terminal guidance systems based on, for instance, GPS or laser target designation already exist and have proven very effective. They can be combined with simple target locators/discriminators and limited terminal guidance for further increased efficiency.

Safety, arming and fuzes in warheads are changing completely from the existing mechanical systems to systems which will use new sensors, linked by electrical circuits and controlled by software systems. This leads to new safety and reliability topics in information technology. Critical software controlling fuzing and function of the warhead in a networked system must be absolutely error free! Initiation based on primary explosives will successively be likely to become less frequent, among other for survivability and safety reasons, and will be replaced by systems such as laser, slapper or EBW (Exploding Bridge Wire) initiators.

OTHER TRENDS

One important trend of today is the increased use of electric energy and in particular the use of pulsed power applications on combat platforms. Concepts such as AECV (All-Electric Combat Vehicle), AES (All-Electric Ship) and MEA (More Electric Aircraft) are emerging. Vehicles, ships and aircrafts are using more and more electric energy for continuous or nearly-continuous consumption for propulsion, vetronics and avionics, air conditioning, laser weapons, etc. Also weapons and protection systems based on pulsed power are emerging, creating new possibilities for weapon systems and ballistics. Some examples are:

- High-Power Microwave (HPM) weapons for disrupting and destroying electronic equipment.
- Electrothermal ignition of LOVA-propellants in guns.
- Electrothermal-chemical propulsion
- Ram accelerators
- Electromagnetic launch of missiles, projectiles, etc. - railguns
- Electric Armour, especially for protection against shaped charge jets

When integrating such systems on platforms, energy and power management will be a critical issue.

CONCLUSIONS

- Metallic hydrogen, with a relative “performance” of about 30 times that of HMX may be seen as the optimal (“chemical”) energetic material.
- Evolutionary development of energetic materials in the 1990s enables a 20-60 % increase in weapons systems performance in the near future.
- Muzzle energies for fielded medium and heavy gun systems might be possible to augment by up to 50 % in the longer term[1].

[1] In many cases recoil will be the limiting factor. The entire gun system will have to be considered!

- Muzzle velocities of 2000 m/s and above may be regularly attained for high-performance systems such as tank guns.
- Air-breathing propulsion, such as ramjet, scramjet, PDE can give performance improvements of up to about 500 % relative to a rocket.
- Base-bleed can give range increases of up to about 40 %, with increased precision and less wind sensitivity.
- Higher muzzle velocities, optimal aerodynamic shapes, ramjet propulsion or fly-out solutions can give range increases of several 100 % relative to normal ranges.
- Penetration in RHA of HEAT (shaped charge) warheads for qualified missile applications might be possible to increase by up to 50 % in the medium term[2].
- A future man-portable AT system may get frontal attitude penetration capability.
- For air-bursting or underwater warheads use of the surrounding ambience for an oxidiser may increase the available energy by about 500 % relative to current explosives
- Protection afforded by modern armours, which include reactive and active components may increase by 100 % or more.
- Design of an "interface defeat" armour may obliterate all threats with velocities up to 2000 m/s
- The level of intelligence and computational power in weapons and munitions may continue to increase by "Moore's Law", by a factor of 100 % per 1 ½ years!

One important conclusion is that, of course, the future will build upon the recent past – a past for which many accomplishments were highlighted in or introduced at the International Ballistic Symposia – and that the future changes in Ballistics will require scientists dedicated to long careers to see their efforts becoming effective in 20 to 40 year timeframes.

With new armour and weapons concepts, like electric armour and HPM-systems there will be more and more multi-physics problems, such as fluid-structure interaction and coupled mechanical and electro-dynamic effects. For these most complex applications new numerical methods must be developed, going far beyond existing methods in engineering. The ballistic community must and will be one of the main drivers of these developments.

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[2] The implications of complex high precision shaped charge design and its performance against improved armour protection with reactive and active components must be considered!

Finally it is hoped that this exposé has shown that the sciences concerning weapons, warheads and ballistics are no longer that mature, that many new options exist and increasingly demand much more research and very advanced design and engineering. Any nation that will abstain from following and participating in these new developing areas will run the risk of having weapons, munitions and protection systems that may prove inadequate, and of making grave mis-investments in defence materiel.

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NOTATION

ADN	Ammonium dinitramide	MAG	Magnetic accelerator gun, railgun
AECV	All-electric combat vehicle	MBT	Main battle tank
AES	All-electric ship	MEA	More electric aircraft
AP	Ammonium perchlorate	MMC	Metal-matrix composites
AP	Armour-piercing	N_4	Tetraazatetrahedrane
APS	Active protection system	N_5^+	*Linear ion, as of yet unnamed!*
AT	Anti-tank	N_5^-	Pentazolate ion
CFD	Computational fluid dynamics	N_8	Octaazacubane
CHNO	Carbon, hydrogen, nitrogen, oxygen	N_{60}	N_{60}-fullerene
		NC	Nitrocellulose
C-J, or CJ	Chapman-Jouguet	NCGL	Nitroglycerine
CL-20	= HNIW	NG	Nitroglykol
DAS	Defensive aid system	NIMMO	Methylnitratomethyloxetane
DATB	Diaminotrinitrobenzene	NM	Nitromethane
DoD	Department of Defense	NTO	Nitrotriazolone
EFP	Explosively formed penetrator	ONC	Octanitrocubane
EMP	Electromagnetic	OSCE	Organization for Security and Co-operation in Europe
EMP	Electromagnetic pulse	PDE	Pulse detonation engine
ERA	Explosive reactive armour	PETN	Pentaerythritol tetranitrate
EI	Extruded, impregnated charges	PSS	Programmed splitting stick propellants
ET	Electrothermal		
ETC	Electrothermal-chemical	RAMAC	Ram accelerator
EU	European Union	RANS	Reynolds-averaged Navier-Stokes
FCS	Future Combat System	RDX	Hexogen
FOX-12	Guanylurea dinitramide, GUDN	RHA	Rolled, homogeneous armour
FOX-7	Diaminodinitroethylene, DADE	SC	Shaped charge
GAP	Glycidyl azide polymer	SCRAMAC	Supersonic ram accelerator
GPS	Global positioning system	SOFRAM	Solid fuel ramjet
HEAT	High explosive anti-tank (= SC)	TATB	Triaminotrinitrobenzene
HEDM	High energy density material	TEX	Dinitrotetraoxadiazaisowurtzitane
HHTDD	Hexanitrohexaazatricyclododecanedinone	TNAZ	Trinitroazetidine
HMX	Octogen	TNB	Tetranitrobenzene
HNB	Hexanitrobenzene	TNT	Trinitrotoluene
HNF	Hydrazinium nitroformate	TNT	Trinitrotoluene
HNIW	Hexanitrohexaazaisowurtzitane	TPE	Thermoplastic elastomer
HPC	High performance concrete	TTTO	Tetra-n-oxyoktaasanaphtalene
HPM	High-power microwave	UAV	Unmanned aerial vehicle
IM	Insensitive Munitions	UN	United Nations
KE	Kinetic energy	URANS	Unsteady Reynolds averaged Navier-Stokes
L/D	Length/diameter	ZDES	Zonal detached eddy simulations
LES	Large eddy simulations		
LOVA	Low vulnerability ammunition		