TORPEDO WARHEAD DESIGN

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ABSTRACT

This article reviews the two generic types of conventional warhead available for use in torpedoes, namely the Omnidirectional or Blast Warhead and the so called Directed Energy or Shaped Charge Warheads. The consequences of the constraints imposed upon the development, deployment and placement of these types of warheads are discussed in relation to their method of operation and potential target damage mechanisms for both submarine and surface targets. The advantages and disadvantages of each type are discussed.

Introduction

The modern torpedo is simply an automotive vehicle, released from a launch platform with the sole function of delivering an explosive payload to the target. The effectiveness of this weapon has long been recognized. Its potential to destroy the capital ships of the major naval powers brought it to prominence in the late 19th century and its marriage to the submarine has dictated much of the course of naval warfare in the 20th century. The development of the payload, the warhead, has revolved around maximizing the quantity and effectiveness of the explosive. As the quantity of the explosive is invariably dictated by other automotive vehicle considerations such as mass, range and speed, maximizing the effectiveness of the explosive was always paramount. The increasing post-war emphasis on helicopter-based anti-submarine warfare has introduced a division into air-launched (lightweight) and submarine-launched (heavyweight) torpedoes. The lightweight, with a much reduced available mass, intensified the necessity for improved explosive effectiveness.

Whilst the options for improved explosive effectiveness are somewhat restricted, all of them have led to improvement in lethality. This article identifies the three major options and summarizes their contributions to improved lethality. The first two options are obvious, to improve the unit explosive yield and to optimize the placement of the warhead to cause maximum damage. Increases in the unit explosive yield can and have been achieved through changes in explosive compositions and the introduction of new explosives. The juxtaposition of the exploding warhead and the target has been refined, in some cases with spectacular improvements in lethality. However the third option, that of modifying the interaction of the explosive with the target was not considered until the late 1970s. In response to the increasing strength of prospective Soviet submarine targets, scientists at RARDE, in an imaginative burst of lateral thinking, applied proven principles for the attack of armoured fighting vehicles to submarine warfare. The result was the Sting Ray L3 Warhead which further divided torpedo warheads into Directed Energy (DE) and Omnidirectional (Blast) variants. This article addresses the merits of both warhead types in the attack of surface and submarine targets.

Improved Explosives

The common focus of both warhead types is the ability of their explosive contents to produce an explosion. An explosion is characterized by the sudden release of gas at high pressure and, usually, high temperature. In the context of military explosives, timescale will be microseconds with peak pressure in excess of 50 000 lb/in^2 and as high as several million lb/in^2. In practical military terms the gas is generated by special types of burning known as deflagration and detonation. Detonation is the phenomenon of particular interest to the warhead designer. In a detonation the explosive 'burns', that is it undergoes a heat liberating (exothermic) reaction. The boundary of the reaction moves through the explosive generating a shock wave moving at the velocity of sound. In fact, the shock wave can travel three to four times faster than the normal velocity of sound in the explosive. This is due to the shock wave compressing the material in front of it. This enables velocities of up to 9000 m/s to be achieved in high density materials such as the Nitramines (RDX and HMX) which are widely used in modern explosives. The shock wave leaving the explosive affords considerable damage potential. If the shock wave enters a fluid medium, such as the atmosphere or water, the effect is known as blast. Blast is characterized by a rapid increase in ambient pressure immediately behind the shock wave followed by a rarefaction. Blast is basically a function of energy release, the higher the energy release the greater the blast effect. If the shock wave enters a rigid medium it produces a shattering effect. The shattering effect is often known as 'brisance'; it is synonymous with detonation pressure and is proportional to both detonation velocity and the density of the explosive. Both blast and shock are important factors in torpedo warhead design.

The first step in increasing the blast potential of warhead explosives was the introduction of trinitrotoluene (TNT) in World War I. This material is relatively insensitive with a Figure of Insensitiveness (F of I) of 150. It produces a velocity of detonation just short of 7000 m/s at a density of 1.58 g/cm^2. It has a low melting point and can be cast either alone or as a slurry with other materials. Until the introduction of TNT, wet compressed gun-cotton was a typical torpedo warhead filling. It was quickly established that the blast effect could be increased either by the addition of oxygen-rich material such as ammonium nitrate (Amatols) or by the addition of aluminium. The addition of ammonium nitrate enables complete 'combustion' of the carbon and hydrogen within the TNT, increasing the energy output at the expense of brisance. The

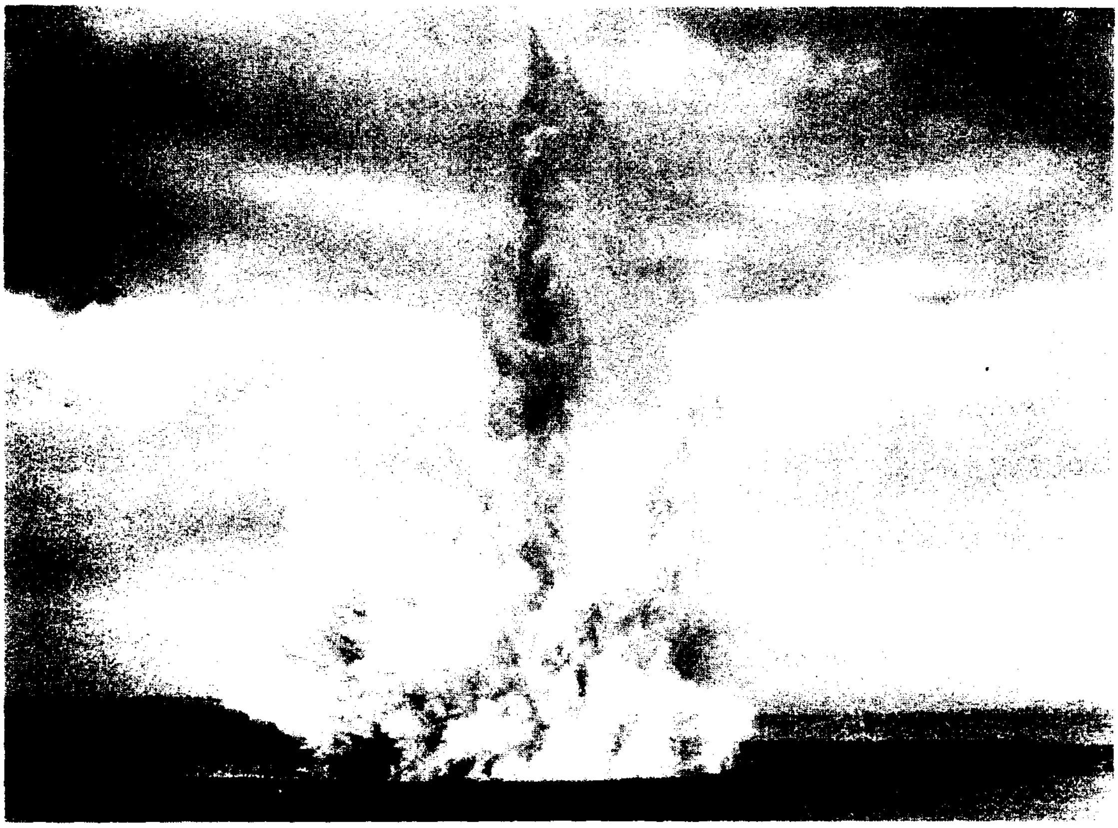

FIG. 1—UNDERWATER EXPLOSION OF A SPEARFISH-STYLE WARHEAD CONTAINING PBX N105

loss in brisance follows from the reduced detonation velocity and reduced density of the amatol. The addition of fine particles of aluminium enables the aluminium to react with the gaseous products of combustion of the TNT (CO_2, CO and H_2O) to form Al_2O_3, H_2 and carbon. This increases the total energy output, again at the expense of brisance. Ammonium nitrate/TNT/aluminium mixtures (Minols) were used to great effect as mine and depth charge fillings. Although TNT-based explosives were very energetic they were not considered sufficiently brisant and a great deal of research undertaken between the wars attempted to retrieve this loss of brisance. The result of the research was cyclotrimethylenetrinitramine (RDX) with a six-membered ring structure of alternate carbon and nitrogen atoms. This is a very powerful explosive with a velocity of detonation of 8400 m/s at a density of 1.7. In later years the higher molecular weight HMX with an eight-membered ring was introduced with a velocity of detonation of 9100 m/s at a density of 1.85. Both of these two explosives are too sensitive to be used alone but RDX in combination with TNT and aluminum gave rise to the very successful Torpex range of explosives.

A typical torpex is 60% more powerful than TNT with velocity of detonation in excess of 7000 m/s at densities around 1.7. Torpex was used in the Mk. 8 and Mk. 24 torpedoes and Torpex 9 will be used in some of the new Spearfish weapons. In terms of energy/unit mass the Torpex type warheads remain unsurpassed in UK service simply because the more powerful plastic-bonded explosives (PBX) have not been cleared for service use. Typically a PBX contains aluminium and ammonium perchlorate encapsulated in a plastic matrix. The plastic may itself be an energetic material. During the development of the Spearfish warhead, PBX N105 was evaluated and a Spearfish style warhead was detonated underwater at ARE Weston (FIG. 1). The normalized (reduced) Energy Flux Density was 29% greater than Torpex 9 whilst Maximum Pressure was 15% greater.

Improved Positioning

The importance of correct placement arose from an analysis of the damage inflicted on surface vessels by influence-fused, non-contact ground mines in comparison with the damage resulting from activation of contact mines. The significant difference in damage potential was confirmed by tests on redundant naval vessels in which charges of the same size were fired, in some instances in contact with the hull, and in other cases beneath and not in contact with the keel. In most instances the under-keel, non-contact explosion produced near sinking damage as a result of the whipping effect on the ship's hull. This whipping is caused by the oscillating gas bubble generated by the explosion and can lead to breaking the back of a surface ship. The oscillating gas bubble is a unique feature of underwater explosions. The gas released by the detonating explosive forms an expanding bubble. The bubble expands until external water pressure exceeds internal gas pressure at which points the bubble collapses compressing the gas under the influence of water pressure. This results in successive expansions and contractions of the gas bubble each of diminishing energy.

The whipping effect is not the only damage-creating factor. Each successive pulse will inflict shock damage on a hull already weakened by the initial shock. The gas bubble will move towards the surface due to the hydrostatic pressure gradient. Both this movement and the hydrostatic pressure gradient itself will change the shape of the bubble, leading to the formation of a jet of water as the bubble collapses. The jet moves upwards through the bubble and eventually appears at the surface. If this jet impinges on the target it can induce considerable damage.

The need for optimum placement leads to two problems for the torpedo designer, namely navigation and fusing. For optimum effect against a surface target the warhead should be detonated between 3 and 8 m beneath the central third of the keel.

The devastating effect of non-contact underwater explosions was emphasized by the damage to USS *Princeton* during the naval operations supporting Desert Storm. Provided that the standoff is not excessive the other effects of the explosion, the hull shattering effect of the shock wave and the shock-induced damage to equipment and personnel aboard the target, do not seem to be reduced.

Provided the warhead detonates sufficiently close to the pressure hull most torpedo warheads, either heavyweight or lightweight, will rupture the pressure hull. Whipping and jetting do not appear to feature significantly in the lethality assessment of anti-submarine weapons. (This is probably due to the complexity of the mathematical models required and the high cost of their validation.) Unfortunately shock and blast effects fall off rapidly with distance and a number of factors conspire to prevent detonation of the warhead in contact with the hull. The first factor is relatively minor. In modern torpedoes the guidance system is in front of the warhead producing a standoff from the pressure hull, albeit small. The second factor is the structure surrounding the pressure hull against which the torpedo will detonate. This standoff can be several metres in the case of large Soviet submarines. This is sufficient to reduce severely the effectiveness of a lightweight torpedo warhead with, say, 40 kg of explosive.

Directed Energy (Shaped Charge)

In 1888 Charles Munroe observed that the damage potential of an explosive in contact with a hard surface could be increased significantly by pressing a cavity into the face of the explosive. Munroe noted that the shape of the cavity, typically a cone or dome, would be imprinted in the hard surface. The mechanism of this phenomenon is akin to refraction in light. In refraction the velocity of light is reduced in an optically denser medium which causes the wavefront to be slewed around towards the normal. With a shock wave, velocity is a function of density and as the explosive is more dense than the air in the cavity the velocity will fall as the shock front enters the air. As the shock wavefront velocity falls it slews towards the normal. In the case of a conical cavity this tends to concentrate the shock effects along the cone axis, thus increasing the damage potential see (FIGS. 2 and 3).

Munroe's discovery was not widely exploited until after World War I at which time it was found that lining the cavity with metal, usually copper or aluminium, increased still further the damage potential. The damage mechanism is broadly the same with a lined cavity as with an unlined cavity. In the lined cavity case, the metal is directed towards the axis where it collides with metal from the opposite side of the cone. The collision causes the metal to flow in two directions. The bulk of the metal flows backwards towards the apex of the cone forming a solid slug. The remaining metal flows away from the apex along the cone axis forming a jet or even a stream of discrete particles moving at high velocity. The sequence of events is illustrated in FIG. 3. The velocity of the jet is of the same order as the velocity of detonation. In simple terms, the target damage mechanism is the high kinetic energy of the jet or particle stream. The mechanism is more complex than suggested, being strongly influenced by cone angle and the shape of the wave front impacting the cavity.

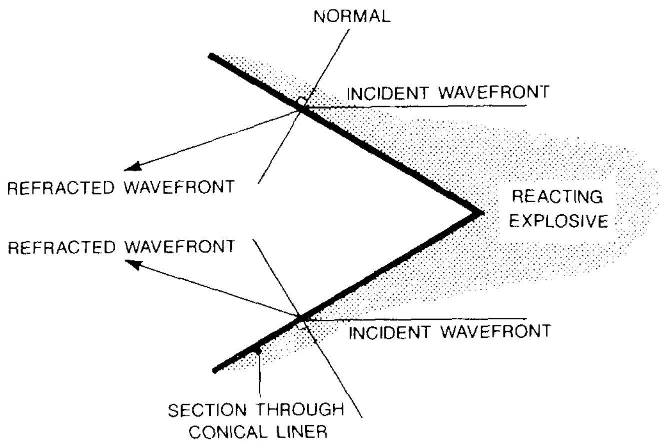

FIG. 2—SHOCK WAVEFRONT REFRACTION

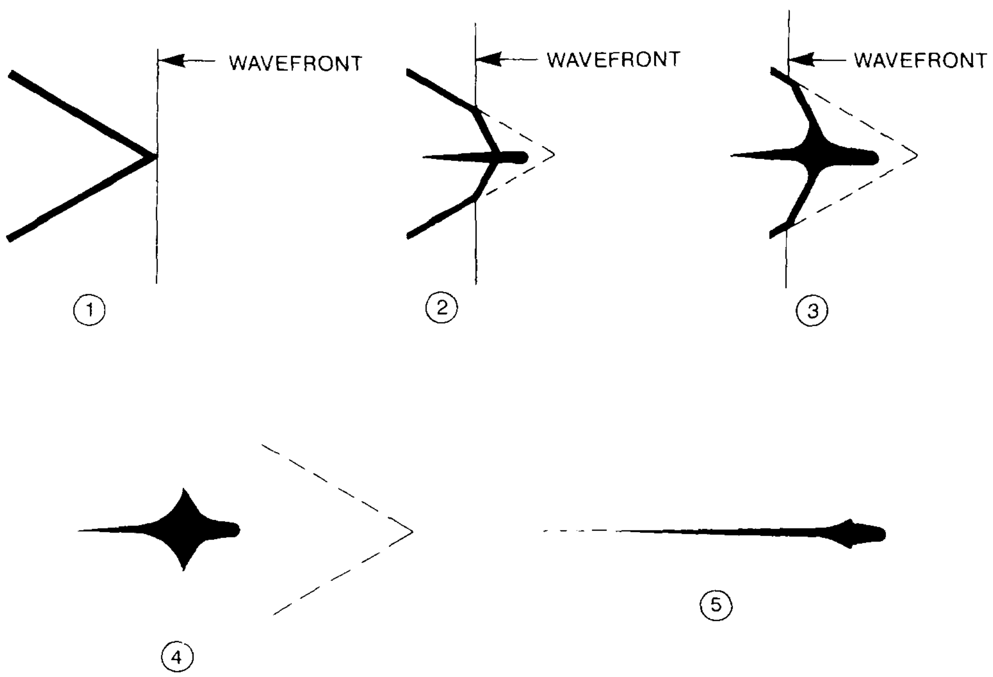

FIG. 3—JET FORMATION WITH A SIMPLE CONIC LINER. TIMEFRAME IS MILLISECONDS

During and since World War II the lined cavity or shaped charge effect has been widely used in the attack of armoured fighting vehicles. It has been found that end-initiated cylindrical explosives charges are less efficient than charges which are tapered towards the initiator (see FIG. 4). Most small diameter warheads are shaped in this way. This effect is probably because a plane rather than spherical wavefront is less susceptible to reflection and scatter and a wavefront which conforms with that of the cavity is even less susceptible. At a sufficiently large radius even a spherical wavefront will approximate to a plane. The jet also requires a clear space in front of the cone in order to form correctly. This can be a real problem in guided weapons as the guidance system is usually placed directly in front of the warhead thus depriving the jet of the vital space needed for its full development. For a particular shaped charge, the penetration of the jet into a material is inversely proportional to the square root of the density of the material. The depth of penetration is usually several charge diameters in typical military target materials such as steel. The pressure of detonation of the explosive is significant in determining target penetration. Pressure of detonation is proportional to the density of the explosive and the square of the velocity of detonation. Good 'shaped charge drivers' such as the EDC family have high levels of nitramines HMX and RDX as well as TNT.

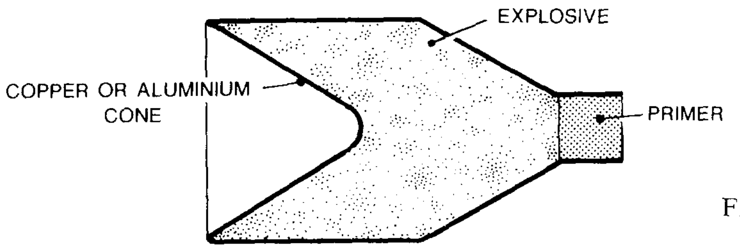

FIG. 4—TYPICAL SHAPED CHARGE WARHEAD

Blast Warheads for Underwater Weapons

For surface targets maximizing shock and bubble energy are the sole concerns for warheads detonated beneath the keel. These factors are dictated by the mass and energy output of the explosive. For surface targets up to about 10 000 tonnes a mass of explosive equivalent to between 150 and 200 kg of TNT will give an acceptably high probability of causing sinking damage. The reduced velocity of detonation of 'blast' explosives limits their use in shaped charge warheads. The converse is not strictly true. High velocity of detonation explosives which do not contain aluminium will have reduced bubble energy and hence a lower probability of causing sinking damage. In the context of large warheads, say above 200 kg of explosive, the lower probability may only be a few per cent.

With contact-detonated warheads a larger explosive mass is required. The UK Mk. 8 torpedo contained 365 kg. of Torpex 2 or 328 kg of the much less effective TNT.

It would appear that lightweight torpedoes have little or no value when deployed against all but the smallest surface targets. If the explosive could be detonated inside the target, rather like the semi-armour piercing shells fired from naval guns, the picture would be quite different. The use of part of a relatively small explosive payload to fire a small warhead into the target which would detonate after penetration has been adopted in airfield denial weapons. Whether relatively expensive torpedoes fitted with this type of warhead would be cost-effective is another matter, as cheaper weapons such as missiles can be fired from the same platforms.

The major damage mechanism for submarine targets is generally regarded as shock-induced rupture of the pressure hull. For each design of submarine a shock factor will be defined. In the event of the submarine experiencing a shock factor above this defined level there is a high probability of hull rupture. The Shock Factor experienced by the submarine is the square root of the normalized (TNT equivalent) explosive mass divided by the distance of the hull from the centre of the explosion. In SI units shock factor will be expressed in $\sqrt{}$kg/m. Suppose the target submarine were designed with a hull rupture shock factor of between 1 and 5. FIG. 5 shows how critical stand off can be in relation to shock factor and warhead mass. (Contact detonation will occur against the casing which dictates the stand off.) In order to define an effective warhead explosive mass an estimate must be made of the stand off and hull rupture shock factor. The hull rupture shock factor will decrease as the target depth increases. A warhead lethal at deep diving depth may be ineffective at periscope depth. In the case of a lightweight torpedo an explosive mass budget of around 40 kg is not unreasonable. The reader can assess its potential effectiveness.

It is also possible that submarines may be susceptible to whipping and bubble jetting as are surface targets.

Shaped Charge Warheads for Underwater Weapons

Suppose a shaped charge were employed instead of the blast warhead. How would it perform? Assuming three charge diameters penetration in steel a 25 cm diameter shaped charge would penetrate 0.75 m of steel (density 7860 kg/m^3) or 2.1 m of sea water (density 1025 kg/m^3) (Penetrations can be calculated for combinations in between). Depending on the target parameters for stand off and hull rupture shock factor a shaped charge may present the only chance of hull penetration.

For heavyweight warheads the same considerations apply with a 50 cm diameter shaped charge being capable of penetrating 1.5 m of steel or over 4 m of sea water. In the case of the shaped charge there may be a penalty to be paid through a significant reduction in the quantity of explosive within the mass budget. As the heavyweight torpedo will be required to have dual capability against surface and submarine targets this can be an important factor. A simple 60° cone is probably the most effective shape for maximizing penetration but is the least satisfactory volumetrically (see FIG. 4). This would be compounded if

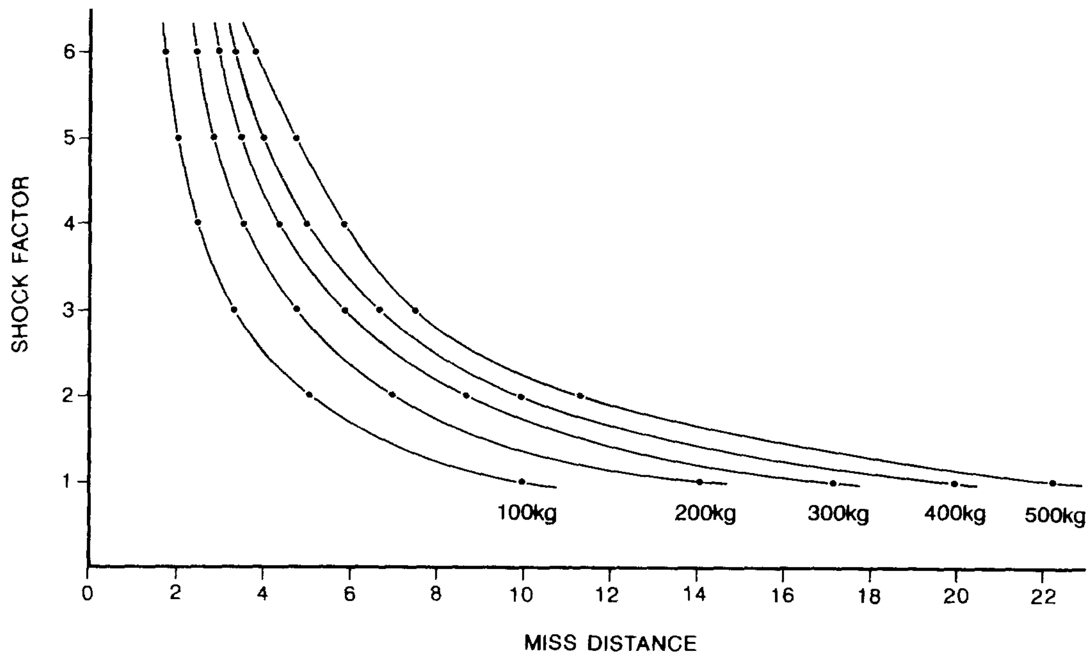

FIG. 5—VARIATION OF SHOCK FACTOR WITH WARHEAD MASS AND MISS DISTANCE

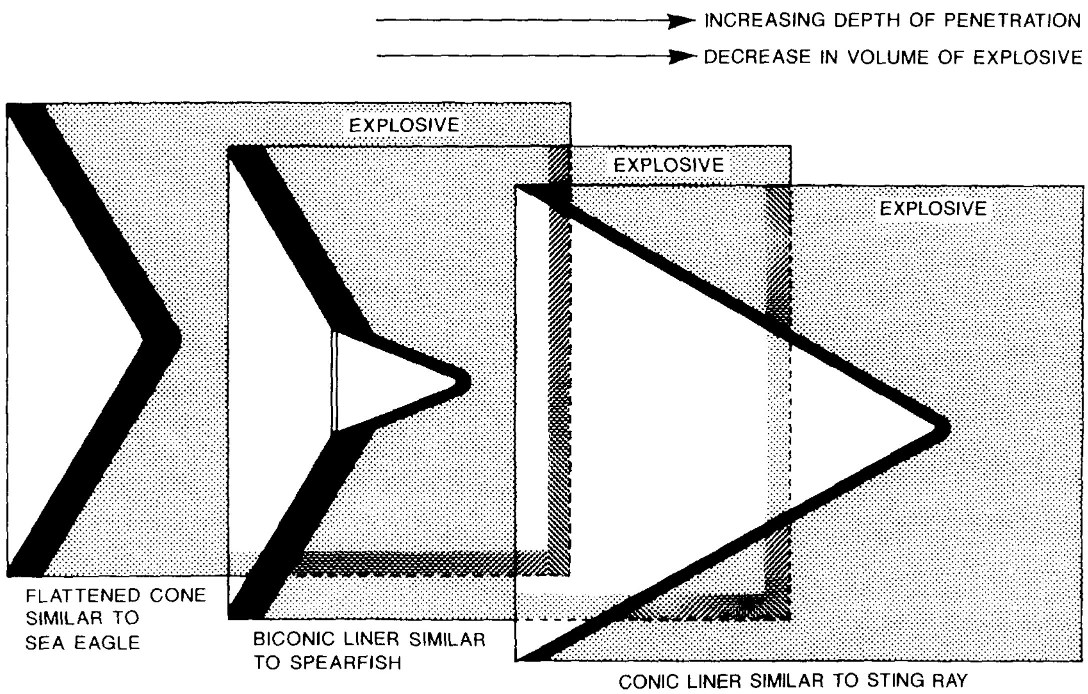

FIG. 6—LOSS OF EXPLOSIVE VOLUME DUE TO SHAPED CHARGE

the explosive were tapered towards the initiator. The use of a thicker, flatter 120° cone would overcome some of these problems at the expense of jet velocity (see FIG. 6). A thicker flatter cone would also require a greater clear space in which to develop. A compromise using a combination of both types of cone offers scope for rapid formation of a traditional jet from a 60° cone to clear a space for the slower forming jet from a thick flat cone, e.g. a biconic shaped charge of the form suggested in FIG. 6. The inner 60° cone is not a complete solution and the formation of the jet from the outer cone is severely hindered by the nose section of the torpedo. The interaction with the nose section reduces the mass of metal available for jet formation and hence reduces penetration. The flatter cone angle also reduces penetration but increases the diameter of the hole produced in the target.

The problems of the shaped charge do not end with interaction with the nose section. The angle of torpedo impact with the submarine casing dictates the direction taken by the jet. As can be seen from FIG. 7, the consequence of some impact angles is that the jet misses the pressure hull. This imposes an additional navigational constraint on the torpedo designer which is not present with a blast warhead.

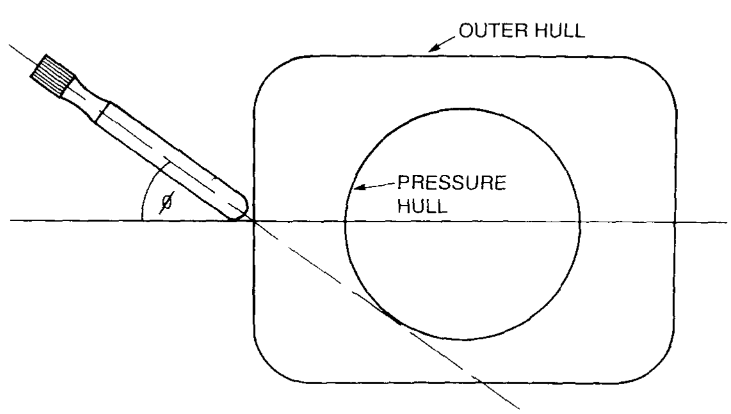

FIG. 7—LIMITING ANGLE OF SHOT LINE FOR HULL PENETRATION. THE SUBMARINE INTERHULL SPACE WILL BE CLUTTERED WITH FRAMES, TANKS AND EVEN MISSILE TUBES

Which Warhead?

For a lightweight torpedo there is little choice. A shaped charge warhead will always have greater potential against submarines. Lightweight torpedoes are not particularly effective, either in cost or lethality terms, against surface targets.

As regards surface targets, with heavyweight torpedoes, there is an advantage for the blast warhead particularly if it is filled with a PBX. With torpex type fillings and allowing for the greater density of good shaped charge drivers, the difference in performance is not significant but the difference in cost may well be. For submarine targets, target definition is all important. Only those targets with a high hull rupture shock factor and large casing stand off present a real challenge. In these cases damage mechanisms other than hull rupture may be significant but these are difficult to model. The performance of a shaped charge can be demonstrated and its effect on the target can be accurately modelled; as accurately, that is, as knowledge of the target permits. These other effects include whipping and bubble jetting, crew survivability and effectiveness under shock conditions and the effect of shock on essential propulsion, control and weapons systems. Finally, the shaped charge warhead will be more expensive but not significantly so as a proportion of the whole weapon cost.