The Application of an Innovative Grenade Warhead to Defeat Combat Body Armour

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ABSTRACT

An innovative grenade concept has been devised to defeat combat body armour (CBA) and produce multi-fold increase in area of effectiveness compared with conventional grenades. The directional warhead of the concept is detailed and its integration within a practical hand-grenade is discussed. Test firing of a development warhead exhibited ample overmatch against the titanium-faced aramid combat body armour as defined in STANAG 4512 for the protected human target, and the prototype warhead has demonstrated the ability to defeat the CBA in excess of 5m radius from the grenade with potentially lethal effect at much greater distance.

A computer code designed to assess the effectiveness of conceptual fragmenting warhead systems against personnel arrays was accessed by a permutation scheme to determine the optimal configuration for the hand grenade: these computational methods are described. Analysis of the hand grenade using the JMEM assault 30 second criterion for incapacitation against targets both with and without combat body armour is presented and compared with results for the M26 grenade. Additionally, a method was proposed for assessing 'instantaneous' incapacitation to accord with the NATO CRISAT TA2 requirements for close combat weapon effects: the method and results as applied to this warhead are given.

The analysis also addresses the need for thrower immunity to the grenade, prevention of a long-range hazard to other personnel, either in training or combat, and changes to the area of effectiveness in the event of misalignment of the warhead.

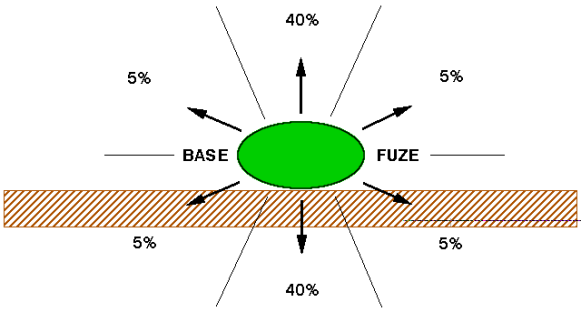
Finally, the role of the computer analysis to rapidly assess alternative configurations and constructions to resolve User needs for high performance, minimal dimensions and low cost is discussed with regard to broader applications of this innovative grenade concept.

INTRODUCTION

Background

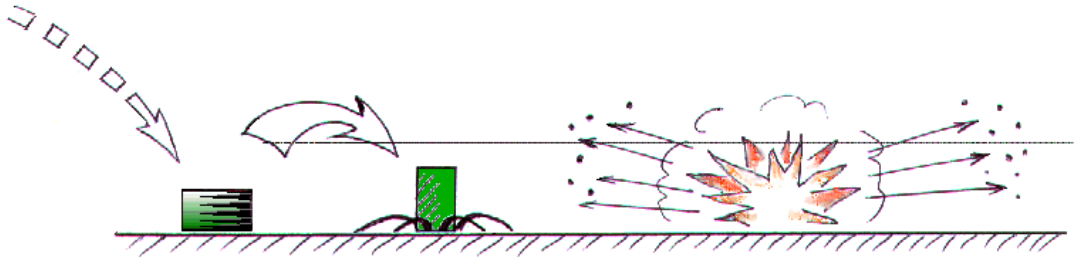
This paper reports on an innovative grenade concept invented by Numerica Limited and includes information based on a collaborative programme carried out under an agreement with Royal Ordnance plc on the prototype incorporation of this concept into the 'Next Generation Hand Grenade' (NGHG). The concept offers performance greatly exceeding that of conventional grenades and is being introduced to Users with a view to reassessing the role of the grenade.

The sketch below illustrates the wastage of fragments downward and upward from conventional grenades, further handicapped by their uneven pattern.



Sketch illustrating the inefficiencies of conventional hand grenade.

The innovative grenade concept avoids fragment wastage by using an axi-symmetric optimal warhead which is orientated by an uprighting mechanism immediately prior to detonation, thereby maximising fragment saturation in the target region, as sketched below.



Sketch depicting the uprighting function and directional warhead of the innovative grenade.

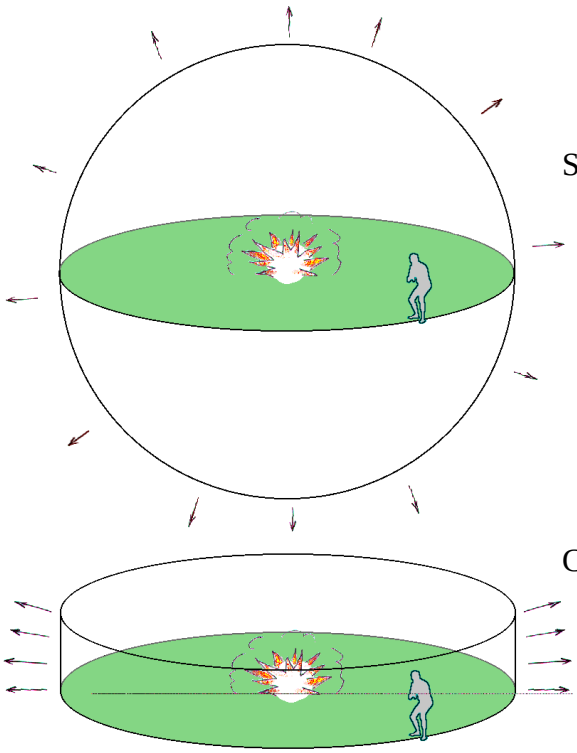
Concept Principles

Whereas a conventional grenade produces a relatively spherical distribution of fragments, the directionality of this innovative grenade concept controls the angles over which the fragments are ejected so that their area of distribution corresponds with the expected location of the target. This maximises the probable number of hits:

$$\text{Probable number of Hits, } P_n = \text{Number of Fragments} \times \frac{\text{Man silhouette area}}{\text{Distribution area}}$$

Example

Consider a man at 5m from a spherical burst, and compare this with a directionally controlled burst in which all the fragments are constrained within a cylinder 2m high at 5m radius. In both cases there are 1000 fragments.



Spherical distribution:

$$P_n = 1000 \times \frac{0.37}{4 \times 5^2} = 1.2$$

Cylindrical distribution:

$$P_n = 1000 \times \frac{0.37}{2 \times 5 \times 2} = 5.9$$

In this example the conventional warhead averages 1.2 hits at 5m: the target effect will be marginal and variable — 30% of targets will be missed entirely.

However, the directional warhead will give five times as many hits at 5m, so producing a greater and more consistent effect. Only a quarter-of-a-percent of targets will be missed.

By matching the fragment distribution to the range, this target-saturation advantage is equal to the range in metres: for example, at 10m the directional warhead will, on average, produce ten times as many hits as the conventional warhead.

The efficiency of the directional warhead enables fewer fragments to achieve greater effect. With a reduced number of fragments, it now becomes practical to use high performance fragments whose high P_{ih} (probability of incapacitation given a hit) is matched to the large radius of target-saturation. These high performance fragments may simply be larger than normal fragments. Alternatively, these fragments may comprise high density material in the knowledge that the investment will not be wasted by a spherical burst, and these penetrative fragments will realise the defeat of combat body armour (CBA) by direct attack.

This innovative concept is particularly suited to:

hand-thrown grenade,

muzzle-launched grenade,

and underslung grenade launcher;

and the fragments could be

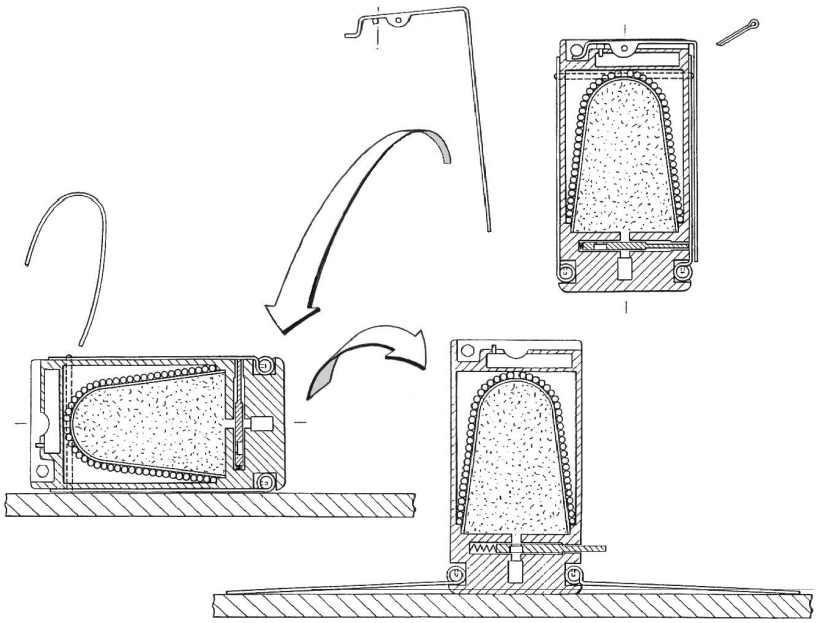
high-density for maximum penetration,

or steel for cost effectiveness.

For convenience, the design and analysis discussions that follow relate to the hand-thrown grenade with tungsten fragments only.

PRACTICAL DESIGN

The functional sequence for the hand-thrown grenade is as follows:



1. The safety pin is removed and the grenade thrown.
2. The fly-off lever immediately detaches and so starts the fuze.
3. The grenade lands and comes to rest.
4. Fuze function-1 at 4 seconds releases the uprighting mechanism.
5. The uprighting mechanism arms the warhead.
6. Fuze function-2 half-a-second later fires the detonator.

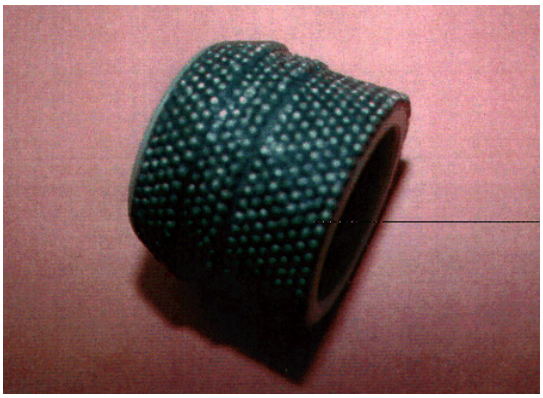
It is anticipated that the two-stage fuze will be either pyrotechnic or electronic.

An uprighting mechanism has been produced and demonstrated to military representatives. Over rough ground with coarse grass and tall thistles the mechanism uprighted the warhead reliably.

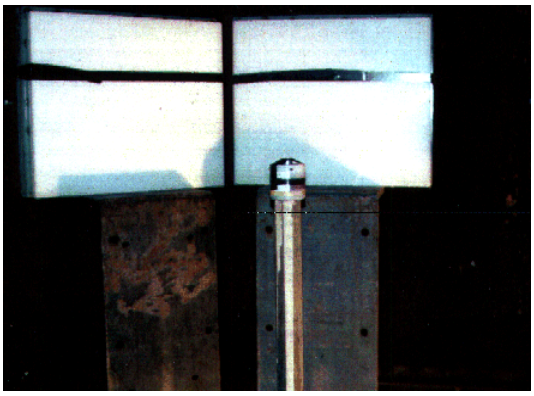
Alternative fuzing and uprighting mechanisms may be used to suit the production engineering preferences.

Prototype Warhead

Various warheads have been produced. The warhead shown was both assembled and tested by Royal Ordnance plc for a 'proof of principle' demonstration. The dimensions of the warhead were determined by optimisation analysis, as described later. In this design, the directional warhead is 'terraced' to maximise its volume within a cylindrical casing.



One of the prototype directional warheads prior to assembly.



An assembled warhead (inverted) with X-ray film packs.

For this test the warhead was elevated to the level of the flash radiograph, and mounted upside-down owing to the limited headroom of the firing chamber. Flash radiography was used to assess any non-conformity with the predicted fragment distribution at the warhead end-faces. A titanium and aramid panel to simulate CRISAT TA1 [1] combat body armour (CBA) was mounted at ground level: in this inverted test this equated to the thorax height of target personnel. Foil detectors were added to record the event timings and so determine fragment velocities.

CRISAT 'body-armour' position relative to the warhead mounting pole.

CRISAT titanium and aramid 'body armour' with foil timing screens attached.

The firings of various prototype warheads showed that the fragment distributions largely conform with those predicted. Only pre-formed tungsten fragments have been used to date, giving principal velocities as expected using modified Gurney equations. The tungsten fragments from a prototype grenade warhead were found to perforate CRISAT combat body armour with considerable overmatch to enable substantial incapacitation effect.

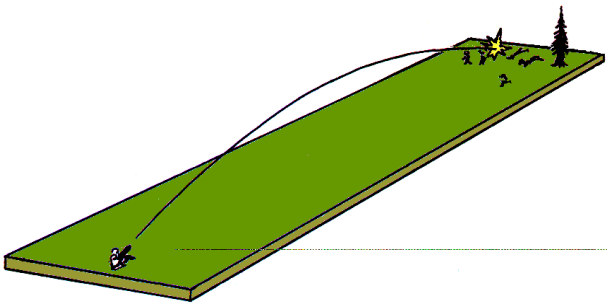
PERFORMANCE ANALYSIS

Method of Analysis

The FragSys code was made available for this analysis by DERA (Fort Halstead) in exchange for the results generated. FragSys code is designed for assessing the performance of fragmenting munition concepts.

Depiction of a FragSys application:

… Shell, grenade or mortar salvos versus target arrays.



A permutation code known as SUG was written to optimise the warhead: this generated target and fragmentation datafiles which were then analysed using FragSys. The performance of the warhead has been optimised on the assumption that 5° of tilt from vertical is likely.

Although the grenade could be gun-launched, the analysis was restricted to the hand-thrown grenade, so the warhead was prescribed to be central in the FragSys target array region.

FragSys uses:

- Shape dependent aerodynamic retardation of fragments
- Kokinasis & Sperrazza [2] determination of the probable incapacitation per hit.
- Variable body armour protection according to body part
- Arrays of target personnel in standing, kneeling, prone and prostrate postures
- Mutual ‘protection’ by overlap of body parts.
- Salvo and accuracy of fire (not required in this case).

As an alternative to ‘Kokinasis & Sperrazza’, FragSys also contains a Rapid Incapacitation Target (RIT) model based on penetrative strikes to the core thorax, neck and head. This extends on an informal method applied in the NATO Personal Defence Weapon study [3].

The analysis results given in the following sections are all produced using FragSys. These results are given as for flat ground: the inclusion of ground undulation will reduce the predicted effectiveness.

Assessment Conditions and Criteria

Comparative Baseline: the US M26 grenade

For performance comparisons, the US M26 grenade was chosen as a baseline. The UK in-service L2A2 grenade is based on the M26.

No comprehensive fragmentation data for the M26 grenade was available. A FragSys fragmentation datafile for the M26 was constructed assuming that there are 1400 cubed fragments each weighing 0.11 grams, launched at 1600m/s and, to account for the lack of near-axial fragments, distributed according to a (cosine(angle from axis))^3 function. The few chunky fragments from the end-casing and fuze are ignored.

Comparison Criteria

Two principal criteria were employed:

1. Probability of Incapacitation (P_i)
2. Mean Area of Effect (MAE) $= \int P_i \, dA$

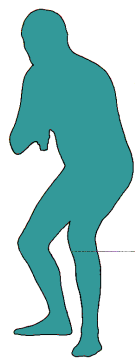
The JMEM criteria for incapacitation were used, which are similar to the Kokinakis & Sperrazza criteria.

The JMEM Assault 30 second and Defence 30 second criteria were used against the intended targets, with the Supply 12 hour criteria being used to assess a grenade thrower's collateral vulnerability.

To estimate the ability to incapacitate within a few seconds, as advised for close combat in the CRISAT TA2 report [4], the Rapid Incapacitation Target (RIT) model was also applied, as detailed later in this paper.

Target Man Presented Area

The area of the man is not defined by the JMEM — it only defines the relative sizes of the body regions. However CRISAT, as invoked by STANAG 4512, defines the area presented by target personnel: for example, the CRISAT crouching man, frontal presentation, 0.37m^2:



The above silhouette was used in this study to allocate the area presented by both the standing man and the kneeling man. As for other postures, the area of a prone man varies according to presentation. To ensure against understating the thrower's vulnerability, the same presented area (0.37m^2) was used for the prone grenade thrower, and the FragSys model's mutual protection of body parts was switched off.

Personnel Protection

Two levels of personnel protection were applied:

1) Light protection

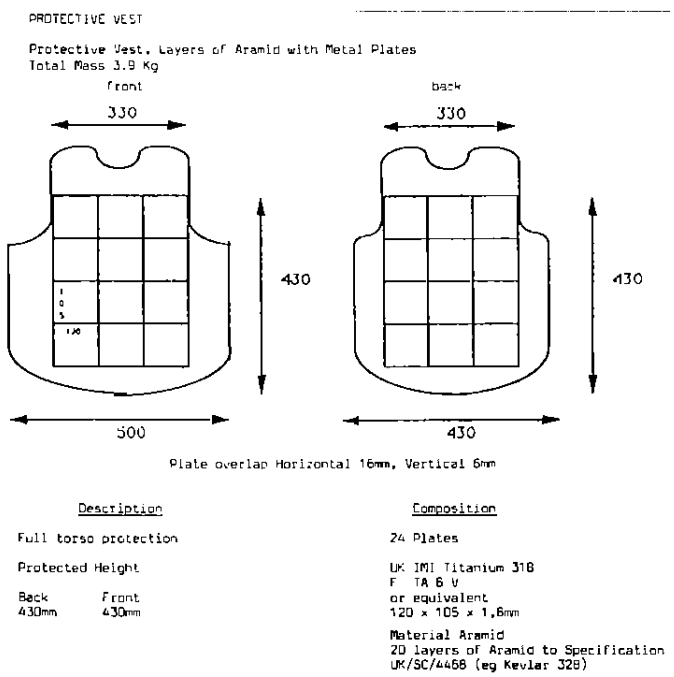
and 2) Combat Body Armour which is *supplementary* to the Light Protection.

Light protection:

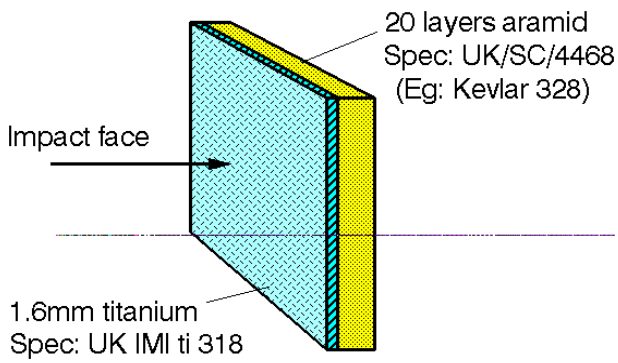
the 'light protection' used in the JMEM is the US 'winter clothing and (metal) helmet' stated in the source data reported by Kokinakis and Sperrazza.

Combat Body Armour:

STANAG 4512 - 'protected human target' invokes the high performance anti-fragment system described in the CRISAT Technical Area 1 'Target Definition' report. This represents the perceived future threat combat body armour (CBA) expected to be worn by opposing infantrymen. The CRISAT representation of the vest is shown below.



The vest armour can be represented as:



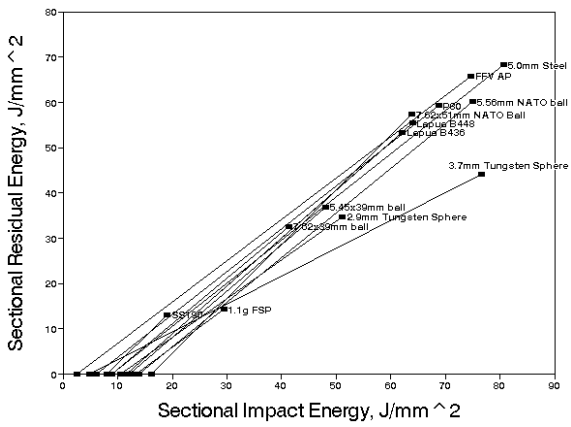
Note, CRISAT combat body armour vest defeats 9mm NATO ball at the muzzle.

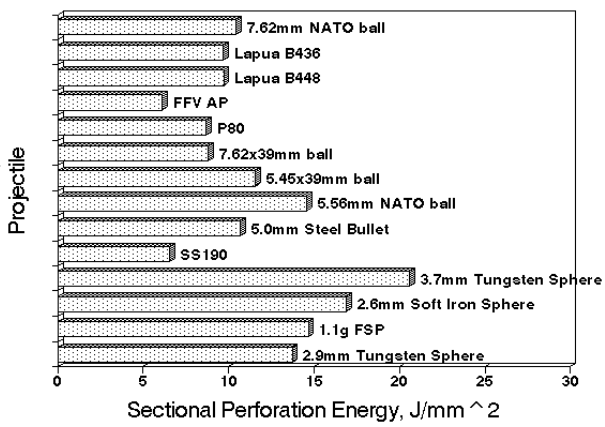
The complete CRISAT combat body armour includes a PASGT type helmet with a 12mm thick polycarbonate visor.

Protective Characteristics of Combat Body Armour

This is the ‘energy per unit area function’ data and plots updated from the study by Allsop & Leeming [5] for the CRISAT combat body armour vest invoked by STANAG 4512 - Protected Human Target.

Projectile	**Slope**	**y0** J/mm^2	**x0** J/mm^2	**Ei/A-Er/A** J/mm^2
2.9mm Tungsten Sphere	0.856	-9.038	10.559	13.718
1.1g FSP	0.881	-11.682	13.264	14.673
2.6mm Soft Iron Sphere				16.910
3.7mm Tungsten Sphere	0.616	-3.008	4.883	20.598
SS190	1.181	-9.427	7.986	6.566
5.0mm Steel Bullet	0.951	-8.534	8.970	10.699
5.56mm NATO ball	0.983	-13.709	13.940	14.582
5.45x39mm ball	1.027	-12.408	12.077	11.584
7.62x39mm ball	1.004	-8.897	8.863	8.800
P80	0.947	-5.755	6.080	8.687
FFV AP	0.912	-2.330	2.555	6.115
Lapua B448	1.053	-12.090	11.481	9.732
Lapua B436	1.052	-12.075	11.478	9.674
7.62mm NATO ball	1.202	-19.377	16.124	10.458



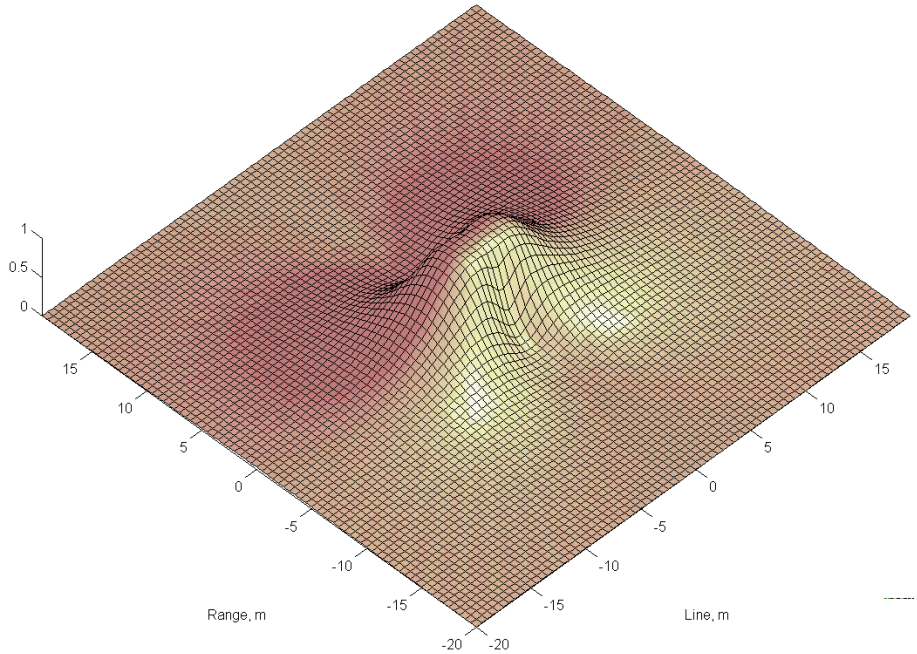


A protection level of 20 J/mm^2 was selected as representative of the protection offered by the CBA vest against tungsten spheres. It was assumed that the helmet and visor will offer similar protection, though no information is available as yet to substantiate this.

ANALYSIS RESULTS

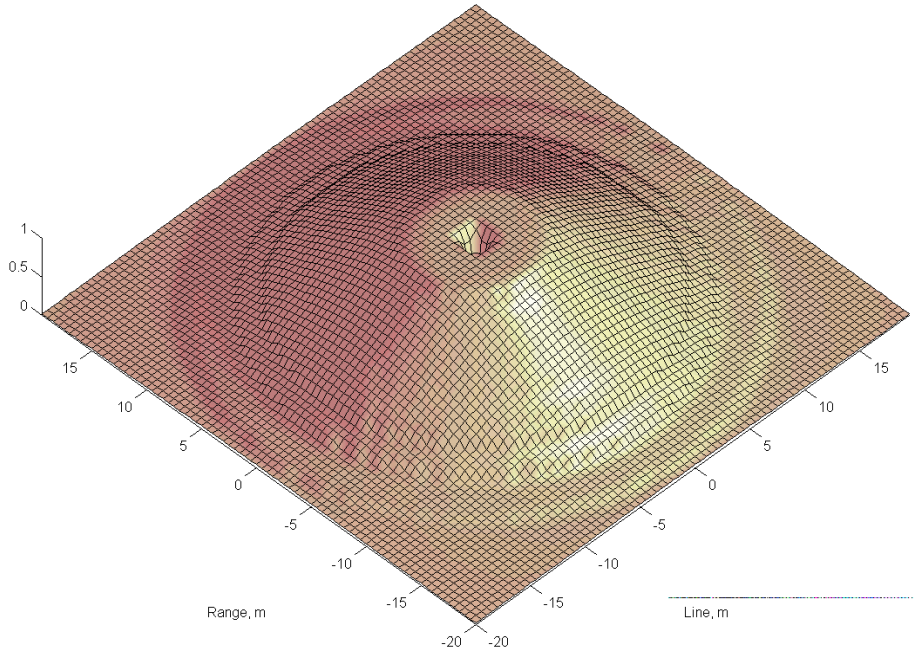
Comparison with the US M26 / UK L2 grenade

Here the Probability of Incapacitation (P_i) is computed over the entire area surrounding the warhead to give the integrated mean area of effect (MAE). First, the baseline performance: M26 versus the lightly protected target:



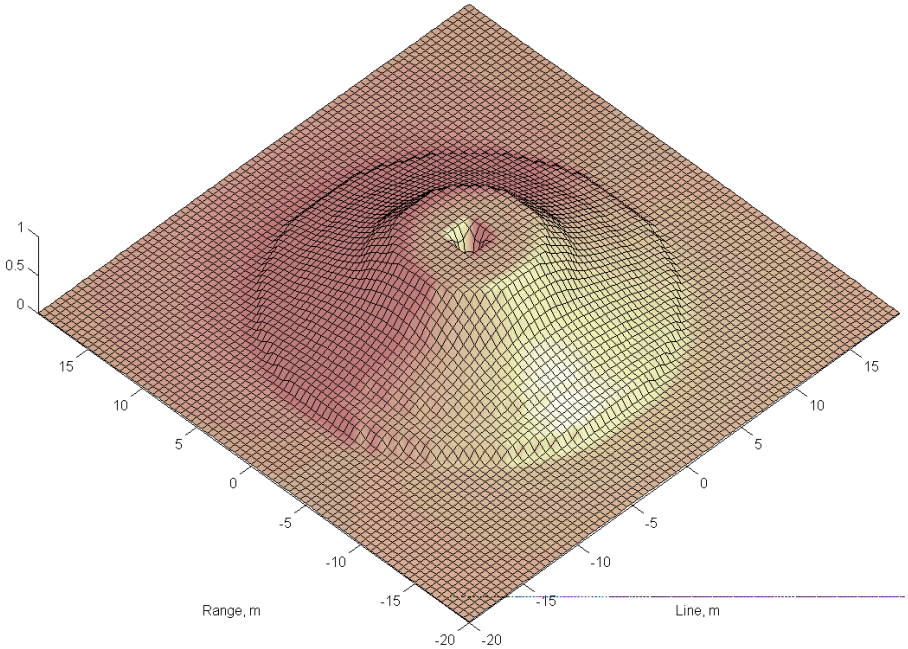
M26 grenade versus standing man in 'winter clothing & helmet' only (no combat body armour), assault 30 seconds criterion. MAE=136m^2

And the corresponding MAE for the 'Next Generation Hand Grenade' (NGHG):



NGHG upright warhead, standing man in 'winter clothing & helmet' only (no combat body armour), assault 30 seconds criterion. MAE=460m^2
(The central void is due to computationally ignoring supplementary high-angle fragments)

Against CBA, the MAE for M26 reduces to 101m^2, and for the NGHG…



NGHG upright warhead versus standing man with CBA protection, assault 30seconds criterion. MAE=314m^2

Summarising the MAE results using the JMEM Assault 30 second criterion, and including a 5°tilt of the NGHG warhead on the basis that the ground is unlikely to be entirely smooth and level:

Protection	M26 grenade	NGHG 5°tilt
Light	136 m^2	482 m^2
CBA	101 m^2	359 m^2

The previous analyses were repeated against standing men at 5m only to give an average probability of incapacitation at this specific radius:

Protection	M26 grenade	NGHG 5°tilt
Light	39%	97%
CBA	29%	95%

Comparative Rapid Incapacitation

The JMEM criteria allow prediction of incapacitation within a minimum of 30 seconds. A shorter time to effect is more appropriate to close combat, hence the Rapid Incapacitation Target (RIT) model. The RIT is based on the rational argument that strikes to certain parts of the head and the core thorax will produce immediate incapacitation. This overlooks modal incapacitation (e.g. a broken arm will prevent certain weapon handling functions) and so the RIT model may underestimate scenario dependent modes of incapacitation.

It is assumed that penetrating injury to the cranium, upper spine, heart, upper major blood vessels or musculature controlling the head and upper spine will assure rapid incapacitation.

Within the RIT model, probability of incapacitation given a hit (P_{ih}) is equal to the predicted depth of penetration into ballistic gelatine as a fraction of a critical penetration, up to a maximum value of one. The only susceptible areas assigned are parts of the head and the thoracic core. Accepting that the head and thorax are only crudely approximated by ballistic gelatine, the critical penetration values were selected by comparison with incapacitating impacts by .22LR bullet and shotgun pellet. The critical values used were:

Body part	Equivalent penetration into ballistic gelatine	Susceptible fraction of body part silhouette
Head	15cm	70%
Thorax	25cm	40%

Repeating the previous MAE analyses but using the Rapid Incapacitation Target model gives, in summary:

Protection	M26 grenade	NGHG 5°tilt
Light	64 m^2	208 m^2
CBA	nil	65 m^2

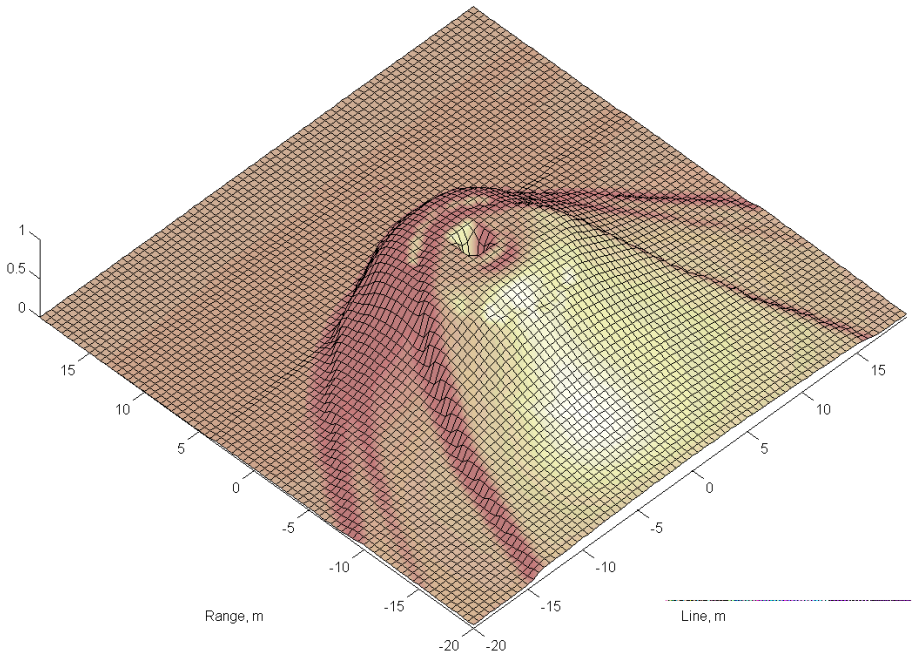
The previous probability of incapacitation analyses were similarly repeated against standing men at 5m only:

Protection	M26 grenade	NGHG 5°tilt
Light	15%	48%
CBA	nil	48%

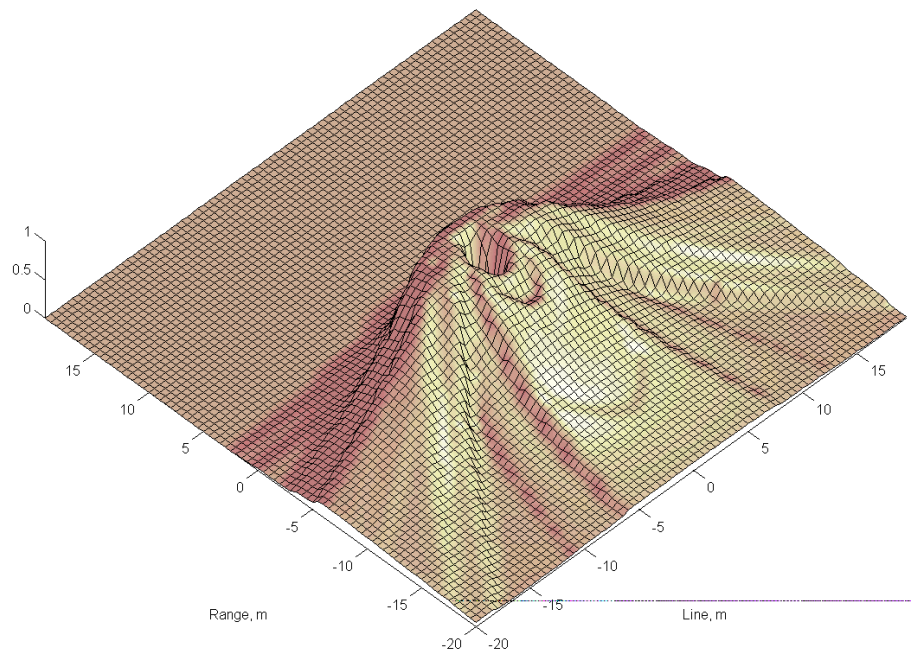
Tilt Sensitivity

The NGHG is dependent on being orientated adequately by the uprighting mechanism. As can be seen in the results below, the NGHG remains highly effective even when tilted at angles of over 15°. It remains superior to the M26 grenade at angles up to 50°.

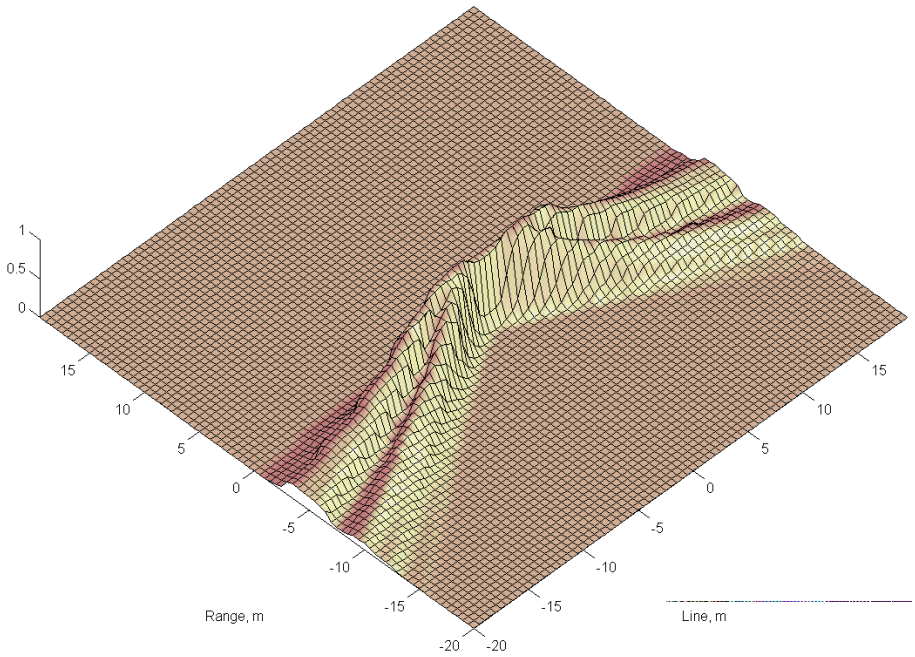
The following sequence shows how the MAE region is modified when the warhead is fired at progressively increasing angles of tilt. The last picture corresponds to the worst case, where the uprighting mechanism fails to operate, so that the grenade in effect reverts to a conventional grenade.



Warhead tilt 5°. Standing man with CBA protection, assault 30 seconds. MAE=359m^2



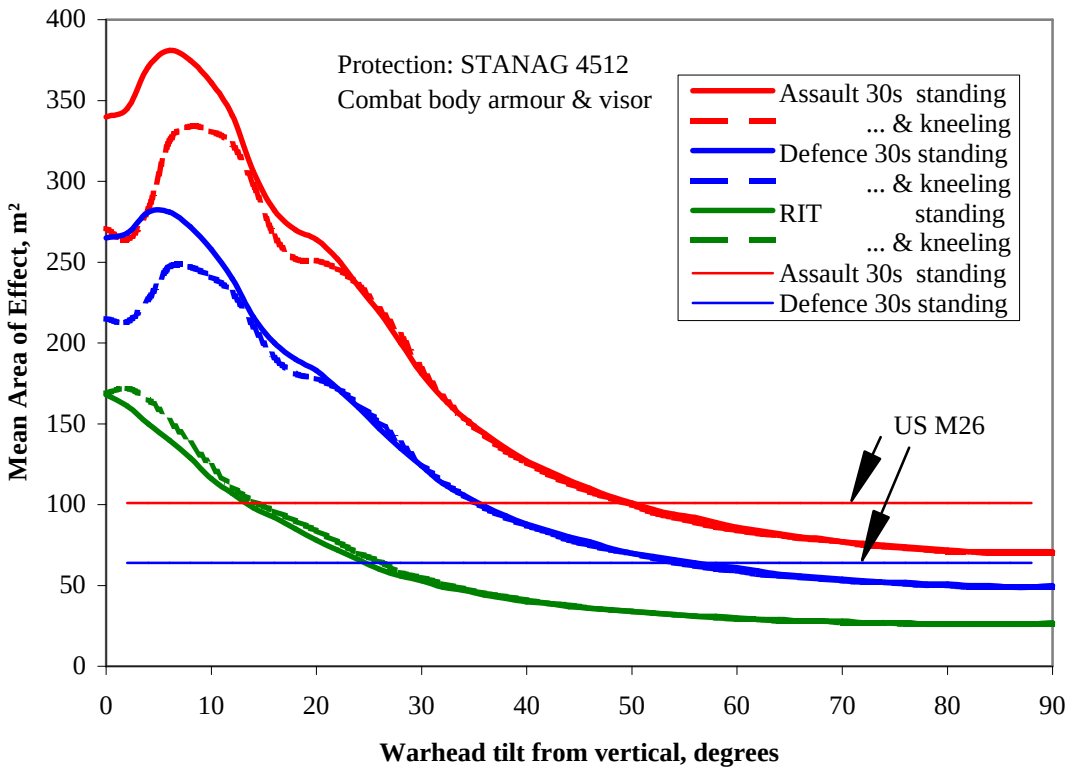
Warhead tilt 20°. Standing man with CBA protection, assault 30 seconds. MAE=254m^2



Warhead tilt 90°. Standing man with CBA protection, assault 30 seconds. MAE=69m^2

In practice, the ineffective regions of the warhead when tilted at 90° would be in-filled at close radius by supplementary fragments and grenade casing fragments so that in the event of failure to upright, the grenade would properly revert to a conventional grenade.

Computing the predicted performance against the CBA-protected target as a function of warhead tilt angle gives the following plots in terms of mean area of effect (MAE):

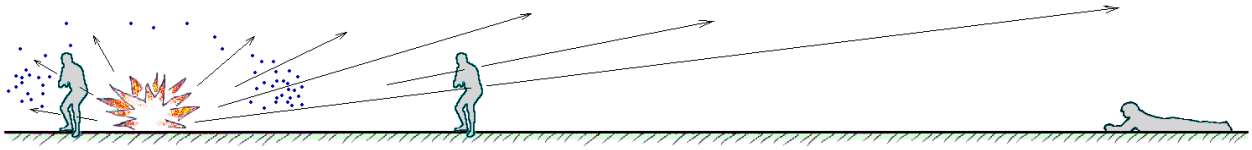


Effect of NGHG warhead tilt on MAE performance against targets with CBA.
(excluding NGHG supplementary high-angle fragments)

Safety Issues

Thrower Safety

With the majority of fragments constrained within the 5° to 25° elevation zone, the majority of fragments pass clear overhead of the thrower.



Sketch illustrating the relative vulnerability of target personnel and grenade thrower.

The large radius of effectiveness does put an exposed thrower at some risk from the grenade: if prone at 20m, the thrower's vulnerability is about 5% (JMEM lightly protected personnel without body armour, 12 hour supply criterion) rising to about 15% with tilt of the warhead. However, the thrower is likely to be protected by ground undulations or obstacles and, regardless of the grenade type, will probably seek immediate cover from enemy fire in such a close-combat scenario.

Safety Trace

For a typical NGHG grenade:

Fragment maximum range≈ 400m where the launch angle is 23°.

As can be seen in the following table, most of the fragments nearly achieve this maximum range. Few fragments are anticipated outside these main fragment-bands.

Launch angle	Fragments in band, approx	Range	Impact velocity	Impact energy (per frag)
2.5°	5%	281m	49 m/s	0.29 J
7.5°	30%	350m	30 m/s	0.11 J
12.5°	30%	378m	29 m/s	0.10 J
17.5°	20%	391m	29 m/s	0.10 J
22.5°	10%	395m	30 m/s	0.11 J
27.5°	5%	393m	31 m/s	0.12 J

Whereas the fragments are each launched with ~200 J kinetic energy, and are thus lethal within the Mean Area of Effect, their landing kinetic energy beyond 350m is only ~0.1J.

STATUS

To date this innovative grenade concept has been applied to only one prototype — the Royal Ordnance plc 'Next Generation Hand Grenade' (NGHG) demonstrator against a UK Ministry of Defence requirement to procure grenades. The concept is applicable to other grenade developments and, as such, is being promoted through the defining multi-national patents (e.g. US patent 5866841, Feb. 2, 1999).

The NGHG concept demonstrator was shown to defeat the CRISAT body armour, and an uprighting mechanism was demonstrated. However a conventional grenade to replace the L2 (US M26 equivalent) was selected by UK MOD: it is surmised that the NGHG was not accepted because:

1. It was decided that, at the defined radius of 3m, a conventional grenade could meet the requirement to defeat a man in CBA by saturation of the limbs rather than by direct attack of the armour.

2. An off-the-shelf solution was preferred: the replacement of grenade stocks was pressing, and the UK MOD are no longer in a position to readily support development programmes.

However, the NGHG offers a performance greatly in excess of a conventional grenade, and as such was presented to UK MOD. The overall dimensions and fabrication cost could have been optimised to suit the User's need, but therein lies the problem: Users have not previously been offered a grenade concept of such potential performance, and this warrants the User to reconsider the role and deployment of hand grenades.

This issue also affects the application of the concept to muzzle-launched, underslung launcher and other grenades types.

SCOPE FOR GRENADE OPTIMISATION

The provisional innovative grenade warhead described in this paper was parametrically optimised for performance against dimensional constraints by use of the SUG computer program. It is anticipated that future applications of this grenade concept will factor both User and manufacturer requirements. These factors are coded into the SUG program for optimisation during permutation of the variable design parameters. For example, the manufacturer may apply cost and production engineering preferences whilst satisfying User needs for size, weight, performance and safety. Once these factors have been coded, the program will determine the optimum warhead configuration within a few minutes runtime. Besides finding the optimum configuration, the program is a useful tool for assessing the design tradeoffs — the study in this paper of sensitivity to tilt is one such assessment conducted using the SUG program.

CONCLUSIONS

The innovative grenade concept offers much greater effectiveness than a conventional grenade, and is capable of penetrating combat body armour. The high path of most fragments affords reasonable safety for the lightly protected thrower, and at long range the descending fragments are non-hazardous.

Its operation utilises a directional warhead in conjunction with an uprighting mechanism, but will revert to a conventional grenade in the event of failure to upright.

It has been proven to perforate CRISAT combat body armour with substantial overmatch to incapacitate the target. A reliable uprighting mechanism has been demonstrated.

The concept is primarily applicable to hand-grenades, muzzle-launched grenades, and underslung grenade launchers, and the fragment materials may be high-density metal for maximum effect, or steel for economy.

Concept analysis by computer code is available to optimise the design according to the User's dimensional and performance requirements, and the production engineering constraints. In view of the capability and scope of the concept, User feedback is invited so as to identify its preferred characteristics and utility.

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