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A SYSTEMS APPROACH TO THE DESIGN OF PERSONAL ARMOUR FOR EXPLOSIVE ORDNANCE DISPOSAL

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ABSTRACT

A qualitative description of the personal armour design system is elicited by comparing armour throughout the ages. Inputs that 'shape' designs are the materials technology, threat, wearer, task and environment. The emergent properties of protection, ergonomic effectiveness and financial cost form the basis of trade-offs to select final solutions.

Work on the protection subsystem refines the key positive emergent property of personal armour. Existing quantifications of protection effectiveness are rejected in favour of a novel measure named the usefulness factor, *UF*. This is the first measure that accounts for the real benefit of armour. A five-stage model is proposed for the assessment of protection. Two feedback loops – due to making tasks as safe as possible and the ergonomic penalty of armour – are evident. These must be considered in order to assess protection correctly. Casualty reduction analysis software (CASPER) is used to produce 'approach plots' and 'zones of usefulness' in order to make tasks safer and map the benefit of armour. This approach is demonstrated with the UK's Lightweight Combat EOD Suit against L2A2 and No. 36 Mills grenades, an HB876 area denial mine, a BL755 sub-munition and a 105mm artillery shell.

Assessment of secondary fragmentation from antipersonnel (AP) blast mines defines a threat input that is specific to Explosive Ordnance Disposal (EOD). Trials are carried out with explosive charges of 50g to 500g, buried under 5 or 10cm of stones and sand at a range of 1m. The threat is defined in terms of the probabilities of (a) being hit, (b) a hit perforating armour and (c) a hit incapacitating an unarmoured person. The chances of being hit close to the ground decrease to approximately 15% of the value when directly above the mine. Secondary fragmentation is not likely to perforate armour that protects against primary fragments. However, it is likely to incapacitate an unarmoured person.

The ergonomic effectiveness subsystem is the primary constraint of personal armour. Visor demisting for the UK's Mk 5 EOD Suit provides a simple example. Existing methods of assessment of the ergonomic penalty of armour are considered. A novel development of biomechanics computational models is proposed to predict both the mechanical and thermal burdens of armour.

Protection is traded-off against proxies for ergonomic and financial cost effectiveness by using quantitative optimisation of personal armour. This introduces the concept of a 'protection optimisation envelope', which defines the bounds of possibility rather than a single solution. CASPER is adapted to produce weight and cost as well as incapacitation parameters. This provides a model that generates both benefits and constraints of armour. Hence, the foundations are laid for the world's first fully integrated personal armour design tools.

Keywords

body armour; casualty reduction analysis; ergonomics; explosive ordnance disposal; optimisation; personal armour; protection; secondary fragmentation; systems approach; usefulness factor.

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GLOSSARY

Symbols

a	coefficient
A	area
A_p	presented target area
A_v	vulnerable area
b	coefficient
C	rate of heat loss by convection
d	depth into target
DOB	depth of burial
E	rate of heat loss by evaporation
E_{saves}	expected number of saves
K	rate of heat loss by conduction
KED	kinetic energy density
m	mass
M	metabolic rate
MAE	mean area of effectiveness
MD	momentum density
MTTF	mean time to failure
n	coefficient; number
n_{hits}	number of hits
$n_{rectangles}$	number of rectangles
P_a	ambient air pressure
P_{hit}	probability of hit
P_i	probability of incapacitation
P_k	probability of a kill: equivalent to $P_{i\ lethal}$
$P_{occurrence}$	probability of occurrence
P_s	maximum overpressure
P_1	point 1
P_2	point 2
P_3	point 3
r	range; spherical coordinate
R	rate of heat loss by radiation; maximum injurious range

R^2	coefficient of determination
s	standard error of regression
S	rate of heat storage
S_1	side 1
S_2	side 2
S_3	side 3
t	time
T	task duration
T_a	ambient air temperature
T_{re}	rectal temperature
T_s	overpressure phase duration
TTC	time to complete a task
UF	usefulness factor
UF^*	usefulness factor for a single section of armour
V_0	velocity at which it is estimated that 0% of projectiles will perforate a target
V_{50}	velocity at which it is estimated that 50% of projectiles will perforate a target
V_L	limit velocity
V_r	residual velocity
V_s	strike velocity
V_{tsh}	threshold velocity for skin perforation
W	rate of external work
x	horizontal range; Cartesian coordinate
x'	differential of x; horizontal velocity
X	angle at which two regions of a blast cone are separated
y	Cartesian coordinate
z	Cartesian coordinate
β	incidence (obliquity) angle for a threat hitting a target
ϑ	angle around a threat; spherical coordinate
ρ	density
ρ_A	areal density: weight per unit area
ϕ	angle over a threat; spherical coordinate
$\$_A$	cost per unit area
$\%CasRed$	percentage casualty reduction

Subscripts

armour	equivalent to *armoured* in this thesis (from an external source)
armoured	with armour
c	equivalent to *casualty* in this thesis (from an external source)
casualty	criterion whereby any hit is considered to cause incapacitation
hit	impact of a projectile onto a target
i	incapacitation
impact recorded	condition of an impact being recorded
lethal	lethal summarised Kokinakis-Sperrazza incapacitation criterion
occurrence	occurrence of an event
perforation	perforation of a target by a projectile
p.f.	primary fragment
serious	serious summarised Kokinakis-Sperrazza incapacitation criterion
s.f.	secondary fragment
unarmoured	without armour
unprotected	equivalent to *unarmoured* in this thesis (from an external source)

Abbreviations & Terms

AIS	Abbreviated Injury Scale
AP	antipersonnel
AT	antitank
BDO	bomb disposal officer
CAEn	Close Action Environment: UK OA computer program
CASPER	UK casualty reduction analysis computer program
CBA	Combat Body Armour
COTS	commercial-off-the-shelf
DCTA	Defence Clothing & Textiles Agency: superseded by DLO DC R&PS
DLO DC IPT	Defence Logistics Organisation, Defence Clothing, Integrated Project Team
DLO DC R&PS	Defence Logistics Organisation, Defence Clothing, Research & Project Support: formerly DCTA
EBA	Enhanced Body Armour
ECBA	Enhanced Combat Body Armour
EOD	explosive ordnance disposal
FELIN	French future soldier technology program

FIST	Future Integrated Soldier Technology: UK programme
FSP	fragment-simulating projectile
GS	general service
HGV	heavy goods vehicle
HV	high velocity
IED	improvised explosive device
IEDD	improvised explosive device disposal
ISS	Injury Severity Score
LV	low velocity
MOE	measure of effectiveness
MOP	measure of performance
NASA	National Aeronautics and Space Administration: US agency
NATO	North Atlantic Treaty Organisation
NBC	nuclear, biological & chemical
NGO	non-governmental organisation
NIJ	National Institute of Justice
N^2	a matrix with N rows and N columns that represents a system
OA	operational analysis
PASGT	Personal Armor System for Ground Troops
PASS	Personal Armour Systems Symposium
PE4	a type of plastic explosive
PPE	personal protective equipment
PSDB	Police Scientific & Development Branch
RAOC	Royal Army Ordnance Corps
RE	Royal Engineers
RLC	Royal Logistics Corps
RPG	rocket propelled grenade
TAB	Trauma Attenuation Backing
TNT	tri-nitro toluene: an explosive
UXO	unexploded ordnance
WIA	wounded in action
WWII	World War II (1939-1945)
UHMW-PE	ultra high molecular weight polyethylene

‘As in life, so in a game of hazard, skill will make something of the worst of throws.’

J MEADE FALKNER
Moonfleet

CHAPTER 1: INTRODUCTION

1.1 OBJECTIVES

- State the scope of this thesis,
- State the rationale for carrying out this work,
- Illustrate the relationships between chapters and thus the path through the thesis,
- Declare that bias towards UK, male, military personnel is *not* a statement on the worth of individual armour wearers.

1.2 THESIS DEFINITION

The purpose of this thesis is to review what makes personal armour 'good' or 'bad' – with specific application to Explosive Ordnance Disposal (EOD) clothing – and therefore demonstrate how it can be designed better. In order to understand this, it is necessary to know what is meant by "personal armour" and a "systems approach." The Oxford English Dictionary (Simpson & Weiner, 1989) defines the individual words as:

"Personal *adj.*	Of, pertaining to, concerning, or affecting the individual person or self…"
"Armour *n.*	Defensive covering worn by one who is fighting;"
"System *n.*	A set or assemblage of things connected, associated, or interdependent, so as to form a complex unit;"
"Approach *n.*	A way of considering or handling something, esp. a problem."

Personal armour can be defined as a defensive covering for the individual who is fighting. However, this includes protection such as a foxhole (a shallow pit dug into the ground). A detailed definition adds that personal armour is man-portable. It is limited to clothing and shields that are carried by the wearer. The benefits and disadvantages of any item can be assessed using a systems approach. This is defined as considering the subject of personal armour as one of several interdependent parts of a complex unit. It is the overall effectiveness (the change in performance) of the system (e.g. the wearer plus all their kit) that defines the worth of any given design. For example, personal armour that is too heavy to be carried is of no use, regardless of the protection it offers. Therefore, *"a systems approach to personal armour* *design" means considering – in order to improve – individual, man-portable, defensive coverings within the context in which they are to be used.*

In order to understand the application used frequently in this thesis, it is necessary to define "Explosive Ordnance Disposal." This is the removal, disarmament or destruction of explosive munitions such as bombs and mines, including devices improvised by terrorists. In its most general form EOD includes dealing with underwater and nuclear, biological and chemical (NBC) threats. However, *the examples in this thesis centre on land-based disposal of conventional (ballistic and blast) weapons as carried out for the UK by the Royal Engineers and Royal Logistics Corps.*

1.3 THESIS RATIONALE

Personal armour plays an important role in the activities of the armed forces and police throughout the western world. It is also used to protect civilians such as bodyguards, VIPs and journalists. One item that is supported by this thesis is the UK's Lightweight Combat EOD Suit (Gotts, 2000). Such developments are showcased at the biennial Personal Armour Systems Symposium (PASS). PASS 2004 in The Hague, Netherlands was attended by speakers and delegates from 25 countries including Austria, Finland, India, Israel, Russia, The People's Republic of China, Serbia & Montenegro, South Africa, Sweden and Switzerland as well as most members of NATO. Hence, *personal armour is a key part of military and security force equipment in developed countries and is likely to remain so for the foreseeable future.*

Current armour solutions range from ballistic vests up to full EOD suits. The latter are designed to offer *a degree* of protection from all the lethal effects of a conventional bomb: blast, ballistic impact and heat. This thesis originates from the UK's Mk 5 Explosive Ordnance Disposal Suit Feasibility Study (Calver, 1995), which concluded that "It is essential that the systems aspects of all aspects of this item are considered from day one. If not, there is a high risk of producing sub-system solutions which are incompatible or which conflict with critical human factors… when used together." Thus, *a systems approach must be used because the armour, wearer and any other equipment must work in harmony if the design is to be successful.*

A recent newspaper article (Shipman, 2002) stated that "British soldiers will have to fight in Iraq with the worst helmets of any army in NATO… The Mark 6 British helmet has a V50 [the velocity at which it is estimated that 50 percent of, in this case 1.1g, fragments will be stopped] of 380 metres a second. But the Kevlar ones worn by their US allies can withstand projectiles travelling at 600 metres a second… They typically weigh one kilo, but the British helmet weighs around 1.5 kilos." While this report is reasonably accurate in its V_{50} and weight facts, it does not present sufficient information to make the statement that British helmets are the worst. For example, there is no mention of what proportion of fragments exceeds $380ms^{-1}$. Neither is there any discussion on factors such as durability, comfort or financial cost. In summary, *it is not only important that designers make armour but that they demonstrate the quality of their decisions.*

1.4 THESIS STRUCTURE

The reader must envisage this work as several snapshots of the personal armour design system and some of its components, each with a given field of view and resolution. Figure 1.1 highlights the system level – from breadth to depth – that is refined in each chapter. The original contribution to knowledge is presented within Chapters 5 to 9.

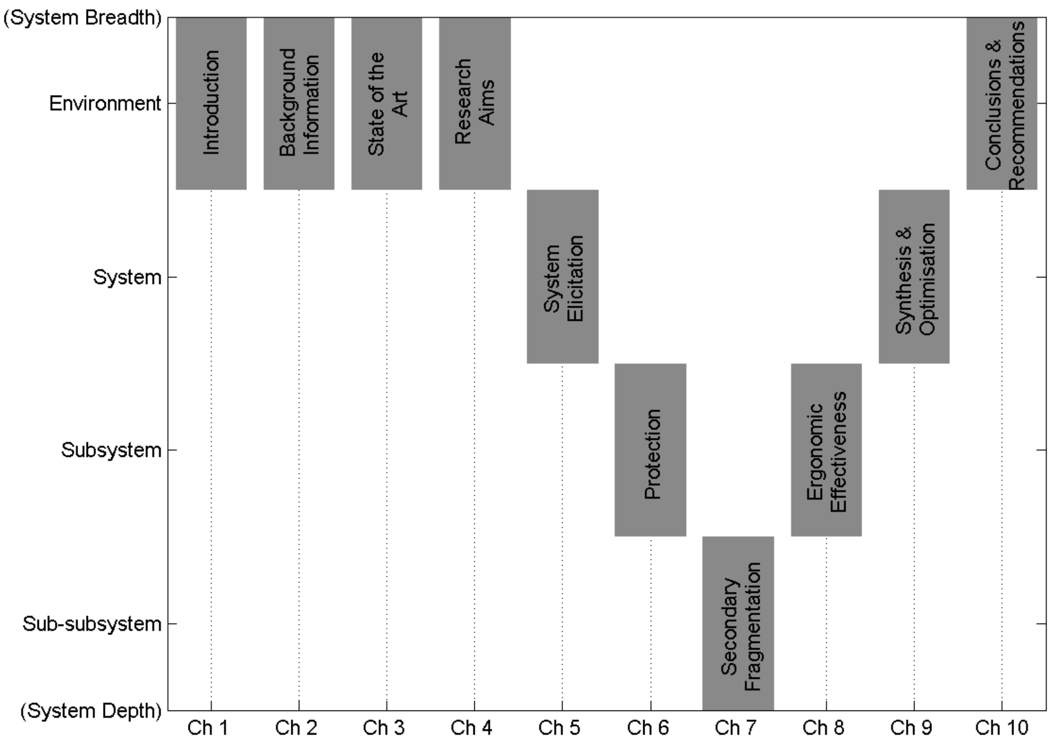

Figure 1.1: System level (breadth-depth) of Chapters 1 to 13

A brief review of the main branches of knowledge that this thesis draws on is presented in Chapter 2. Current personal armour designs are presented with an introduction to EOD activities. The fundamental ideas behind systems theory and systems engineering are then discussed briefly.

Chapter 3 reviews the state of the art in relevant personal armour design topics. This presents the subjects that provide the foundations for this research.

The research aims of this thesis are developed in Chapter 4. The selection of objectives is based on their (i) influence on improved armour design and (ii) urgency for supporting the development of the Mk 5 EOD Suit (Calver, 1995) and Lightweight Combat EOD Suit (Gotts, 2000).

Chapter 5 elicits the personal armour design system by comparing armour throughout the ages. Qualities that remain constant for all solutions define the underlying system. This provides a framework to reduce the system to smaller pieces for refinement in Chapters 6 to 8 and to synthesise it for optimised design in Chapter 9.

The most important subsystem in personal armour design – protection – is developed in Chapter 6. The limitations of current measures of effectiveness are discussed and a novel one is proposed. A model of the subsystem is presented with an example that illustrates the importance of considering feedback when assessing protection. A demonstration of how to improve casualty reduction analysis software is then given. The examples are based around EOD scenarios but the theory applies to any personal armour.

Chapter 7 refines an input to the protection subsystem in order to support the development of the Lightweight Combat EOD Suit (Gotts, 2000). The threat of secondary fragmentation from antipersonnel (AP) blast mines is assessed. Previous work focuses on the blast threat, yet debris thrown up in an explosion can be a significant danger in itself. Experimental data is gathered as supplementary information from an existing set of trials. The results describe the distribution of fragments and their probable effects on a target.

Chapters 6 and 7 refine the benefit of personal armour with specific reference to EOD. However, garments are of no use if they cannot be worn. Chapter 8 explores the ergonomic effectiveness subsystem. This constraint to – rather than driver of – armour design is the major counterbalance against the protection subsystem. Work carried out on a visor demister for the Mk 5 EOD suit is described as an example of ergonomic design. The advantages and disadvantages of current assessment methods and measures are discussed. This is followed by the development of theory for a potential novel use of computational biomechanics in personal armour design.

Chapter 9 uses the measure of protection effectiveness developed in Chapter 6 plus surrogates for ergonomic and cost constraints to quantitatively optimise personal armour. Casualty reduction analysis software is adapted to select a handful of best solutions from over 300,000 options. Examples are based around EOD but the theory applies to any personal armour.

General conclusions of the major findings of this thesis and recommendations for future research are presented in Chapter 10.

1.5 DISCLAIMER

Personal armour is worn by women as well as men in many modern armies and security forces around the world. This provides interesting challenges for the designer such as fitting garments to the female form. In this case the author uses feminine descriptions of the armour wearer such as "woman", "she" and "her." However, the English language does not yet have a readily accepted neutral form to describe the wearer as either a woman or a man. In this case the author uses masculine descriptions including "man", "he" or "him." No bias of the worth of individual soldiers or security personnel is intended.

1.6 CONCLUSIONS

1. The scope of this thesis is to refine knowledge and tools in order to improve personal armour – including clothing and shields – and apply them to the disposal of land-based ballistic and blast explosive ordnance.

2. This work is carried out because personal armour continues to be a key part of military equipment. Specifically, it supports the development of the UK's Lightweight Combat and Mk 5 EOD suits. These require the balance of trade-offs achieved by systems thinking in order to justify design decisions.

3. The path through the main body of this thesis is: (Chapter 5) elicit the system of benefits and penalties that make personal armour 'good' or 'bad'; (Chapter 6) improve calculation of the key benefit of armour – protection; (Chapter 7) detail a limited input to the protection subsystem for the benefit of the Lightweight Combat EOD Suit; (Chapter 8) refine the main penalty of personal armour – ergonomic effectiveness; (Chapter 9) synthesise the system in order to optimise protection against proxies for ergonomic and cost penalties.

4. Examples and language used in this thesis focus primarily on UK, male, military armour wearers. No bias of the worth of individuals is intended.

1.7 REFERENCES

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CHAPTER 2: BACKGROUND INFORMATION

2.1 INTRODUCTION

2.1.1 Aim

To prepare the reader with the basic knowledge of the subjects which dominate this thesis.

2.1.2 Objectives

- Review the types of personal armour that are currently available,
- Describe in brief the roles, tools and scenarios of EOD,
- Introduce a selection of the key concepts of systems theory & systems engineering.

2.1.3 Background

This thesis draws from personal armour design, systems theory and the application of Explosive Ordnance Disposal (EOD). These have become diverse subjects and are therefore summarised briefly in this chapter. They are presented to familiarise the reader with the underlying subjects rather than as a definitive description of all the issues involved. The presentation of EOD and armour in this chapter is biased towards the UK military as a sponsor of this research.

A conference paper has been presented (Couldrick & Iremonger, 2001) that introduces a significant proportion of Section 2.3.

2.2 A BRIEF REVIEW OF MODERN PERSONAL ARMOUR DESIGN

2.2.1 Examples of non-EOD personal armour

A common perception of personal armour for ballistic protection is the ‘bullet-proof’ vest. This is designed to catch low velocity bullets from handguns in soft textile packs. Typical threats used for proof testing (NIJ, 2001, Croft, 2003a) are 9mm full metal jacket and 0.357″ magnum rounds with velocities less than $450ms^{-1}$. Vests can be either overt (Figure 2.1) such as for a uniformed police presence or covert (Figure 2.2) for undercover personnel, bodyguards and VIPs. Both versions offer protection to the torso but overt vests can offer greater resistance because more material can be used than for covert garments, for which reduced bulk is more important.

Figure 2.1: MOD Police wearing overt body armour (picture courtesy of DLO DC R&PS)

Figures 2.2a & b: Covert body armour (a) exposed and (b) covered
(picture courtesy of DLO DC R&PS)

Stabbing with knives and spike-type weapons is a major threat to police officers (Horsfall, 2000). However, bullet-proof vests do not necessarily offer sufficient protection from stab threats due to the different perforation mechanisms involved. Stab-resistant body armour has its own proof testing standards (NIJ, 2000, Croft, 2003b). While such garments are not designed for ballistic protection, they *are* incorporated into dual-purpose body armour. Vests that offer both stab and low velocity bullet protection have to deal with two very different threat mechanisms. This is akin to the duality of ballistic and blast threats involved in EOD.

UK police and soldiers in riot control situations use helmets and polycarbonate shields in addition to protective vests and flame retardant clothing (Figure 2.3). These extra items are designed to offer greater protection against hand-thrown missiles such as bricks and petrol bombs. The shields of several people can be positioned together to form a wall.

Figure 2.3: UK soldiers during riot control training (picture courtesy of UK MOD)

The preceding armour items are not used by EOD personnel because they face different conditions to those for police forces, prison officers, bodyguards, VIPs, etc. However, garment similarities and differences provide a basis for comparison in Chapter 5 in order to validate the personal armour design system.

2.2.2 Examples of general purpose personal armour that is used for EOD

Modern personal armour that *is* used for EOD – as well as general military applications – starts with fragmentation helmets and vests. The former includes the UK's General Service (GS) Mk 6 Combat Helmet (Stilwell, 2003) (Figure 2.4). This provides a degree of protection from battlefield fragmentation and severe impacts e.g. from falling masonry. Its shell is made from multiple layers of ballistic nylon with a shock absorbing liner. It is shaped to maximise coverage, while being compatible with personal weapons, communication headsets and camouflage covers. The Mk 6 has an adjustable suspension system and comes in four sizes. This increases comfort by fitting a wide variety of head shapes and separates the wearer's head from hard surfaces. It weighs around 1.35kg. An adaptation kit is available to add a transparent visor and neck protector. A programme is now underway to replace the Mk 6 (Iremonger & Gotts, 2002) in line with the protection levels offered by other NATO countries that use aramid rather than nylon such as in the US's PASGT helmet (Stilwell, 2003).

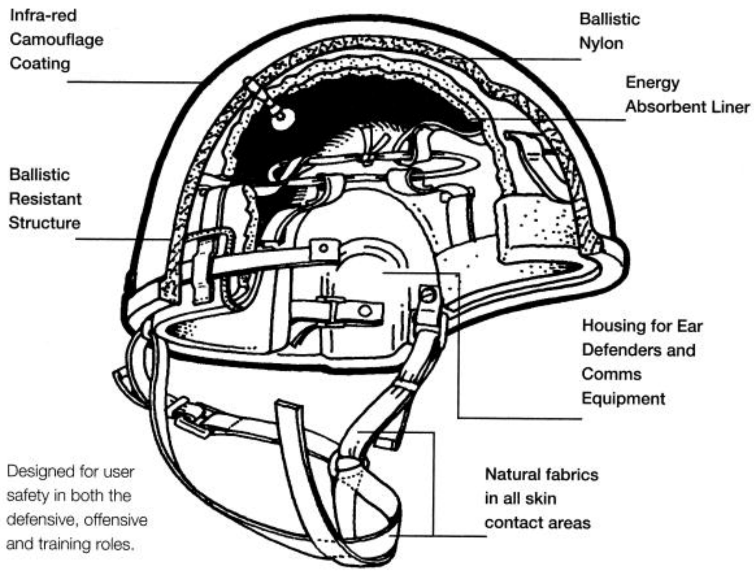

Figure 2.4: UK GS Mk 6 combat helmet (Stilwell, 2003)

The typical companion to the Mk 6 helmet is the UK's vest known as Combat Body Armour (CBA) (Figure 2.5). It offers fragmentation protection over the torso to a V_{50} (the velocity at which it is estimated that 50 percent of projectiles will be stopped) for 1.1g chisel-nosed fragment simulating projectiles (FSPs) (NATO, 1996) of around 450ms^{-1} (Stilwell, 2003) to 500ms^{-1} (Iremonger & Gotts, 2002). It is a compromise between protection and weight (2.5kg for the medium size) so that the wearer may move quickly. Six sizes are available to cover the range of users with five colours to cover temperate, artic, desert, navy and peacekeeping environments. The ballistic protection in CBA – in common with other soft personal armour – can be removed to launder the outer cover.

Figure 2.5: UK troops on manoeuvre wearing CBA, GS Mk 6 combat helmet and goggles while carrying an SA80 rifle and webbing (picture courtesy of UK MOD)

CBA is designed to offer a degree of protection from battlefield fragmentation: the predominant threat in 20th Century warfare (Beyer, 1962). The second biggest threat for soldiers is high velocity rifle bullets (Titius, 2002) such as 5.45 x 39.5mm and 7.62 x 39mm ball rounds fired at around 900 and 700ms^{-1} from AK74 and AK47 assault rifles respectively. CBA on its own is not designed to stop this threat so hard armour plates (Figure 2.7: left) are added for Enhanced Combat Body Armour (ECBA) (Figure 2.6). There are two identical plates for the front and rear. They are made of an alumina strike face with an aramid composite backing. Each plate has a mass of approximately 1.1kg, so are only big enough to cover the heart and the immediate surrounding area. They offer EOD personnel extra protection from heavier and faster fragments than the basic vest but over a limited area of the body.

Figure 2.6: Royal Marine wearing ECBA with the hard armour plates highlighted (picture courtesy of UK MOD)

Figure 2.7: UK ceramic-faced inserts showing the (left) INIBA plate and (right) MOD Police body armour plate (picture courtesy of DLO DC R&PS)

Enhanced plates have been developed by the UK that offer greater protection against 0.50″ armour piercing and 12.7mm armour piercing incendiary bullets (Iremonger & Gotts, 2002). They use a boron carbide strike-face with an aramid composite backing. A Trauma Attenuation Backing (TAB) is placed behind the plate to reduce pulmonary contusions caused by stopping such high energy threats. The plates plus TAB form the basis of the UK's Enhanced Body Armour (EBA).

The armour within this section is not designed specifically for EOD personnel but it is used by them – with the exception of EBA. A helmet plus visor and fragmentation vest is thus the current lightweight (around 5 to 7kg) personal armour option for UK military EOD operators. This offers a degree of protection to the torso, head and face.

2.2.3 Examples of EOD-specific personal armour

The first level of EOD-specific personal armour that offers greater protection than a helmet and fragmentation vest is the medium weight (around 15 to 20kg) of a search or mine clearance suit. This is designed typically for demining or combat operations, where extended usage periods or greater mobility is required. The UK's Lightweight Combat EOD Suit (Gotts, 2000) (Figure 2.8) was designed in parallel with this thesis (Appendices A & B). It is 'lightweight' in comparison with full EOD suits.

Head protection for the Lightweight EOD Suit consists of a helmet, visor, nape protector and commercial-off-the-shelf (COTS) safety glasses. The geometry of the helmet is based on the UK's Parachutist's Lightweight Helmet due to the higher trim line. The 5mm thick polycarbonate visor offers a degree of ballistic protection, while the safety glasses help keep dust, grit and secondary fragmentation from the eyes.

The torso is covered with an aramid vest that resembles ECBA but has a V_{50} for 1.1g chisel-nosed FSPs (NATO, 1996) that is approximately 10% greater. Additional collar, arm and pelvic armour is mounted on a mesh vest worn underneath the jacket, while separate leggings are donned with braces. A pair of fingerless aramid gloves reduces the likelihood of tissue stripping of the hands.

Figure 2.8: Lightweight Combat EOD Suit on trial (picture courtesy of DLO DC R&PS)

A noticeable absence from the Lightweight Combat EOD Suit is that of protection for the feet. Mine boots are a current hot topic of interest (NATO, 2003) because of the difficulty of providing any useful benefit at such close ranges as a foot stepping on a landmine. Current commercial-off-the-shelf (COTS) mine boots provide good examples of three different strategies for resisting explosive threats (King & King, 2004b). UK-based Aigis PPE100 (Figure 2.9a) uses 2.5cm of a proprietary, frangible material named TABRE® to *absorb* blast energy (Chaloner et al., 2000). Canadian MedEng Spider boot (Figure 2.9b) relies on *increasing the stand-off distance* between the mine and the foot. The French Anonymate Mine Boot (Figure 2.9c) has a wedge-shaped sole to try to *deflect* some of the blast energy.

The fourth strategy for resisting blast threats is demonstrated by the UK's Mk 4 EOD Suit (Gotts, 2000, King & King, 2004a) (Figure 2.10). A plate mounted on the front is designed to *decouple* blast energy in the same way that double-glazing reduces noise transmission. This suit is an example of the heavyweight (around 25 to 30kg) end of EOD-specific clothing. It is currently in service in the UK for neutralising unexploded ordnance (UXO) and improvised explosive device disposal (IEDD) i.e. dealing with terrorist bombs.

Figures 2.9a, b & c: (a) Aigis PPE100 boot (King & King, 2004b), (b) MedEng Spider boot (King & King, 2004b) and (c) Anonymate mine boot (picture courtesy of DLO DC R&PS)

Figures 2.10a & b: (a) Mk 4 EOD Suit (picture courtesy of DLO DC R&PS) and (b) MedEng EOD-7B Suit (King & King, 2004a)

The rigid plate covers the thorax, abdomen and pelvis. This is worn over a full suit of soft, relatively flexible fragmentation armour. Head protection consists of a specialist air-demisted helmet and glass-fronted visor. The protection level offered by a full EOD suit is designed to be the greatest possible while still allowing the wearer to work effectively. Nevertheless, in the author's experience, heavyweight suits restrict movement and most require assistance to don and doff. A further issue is that the extra physical exertion can cause the visor to mist up. The COTS approximate equivalent to the Mk 4 is the EOD-7B suit (King & King, 2004a) (Figure 2.10b) by the commercial EOD suit market-leaders MedEng from Canada.

The successor to the Mk 4 is the Mk 5 EOD Suit (Calver, 1995), which has been developed by NP Aerospace of Coventry, UK (Figure 2.11) under contract to DLO DC IPT. It is heavier than the Mk 4 suit at around 30kg but is easier to wear because its joints (e.g. shoulders) are constructed to be more flexible and its weight distribution is close to the wearer's centre of gravity. The Mk 5 and Lightweight Combat EOD Suits form the basis for the majority of the applications in this thesis.

Figure 2.11: Mk 5 EOD Suit (courtesy of NP Aerospace, Coventry, UK)

2.3 A BRIEF DESCRIPTION OF EXPLOSIVE ORDNANCE DISPOSAL

2.3.1 The current threat

The *raison d'être* of land-based EOD is to clear landmines, unexploded ordnance (UXO) and improvised explosive devices (IEDs). These exhibit great variations of distribution, frequency and destructive potential. Nevertheless, the designer must understand the threat in order to specify the best armour for the job. Any threat assessment should consider the position of the threat at detonation relative to people; method of attack e.g. blast wave, small fragments or a single, dense fragment; distribution of attack e.g. 360º or 60 º arcs; frequency of threat.

Landmines and other area denial weapons are designed to prevent access to areas such as roads. They can be classified according to their intended target and method of attack. Jane's Mines and Mine Clearance (King, 2000) provides details on anti-personnel (AP) and anti-tank (AT) landmines. Four main types of AP mine are in current usage. These are blast, fragmentation, directional and bounding. Each one has associated blast, fragmentation, incendiary and anti-tampering characteristics.

AP blast mines (Figure 2.12a) are the most common type of landmine. They are normally surface-laid or buried down to 40mm, to enable them to operate reliably. Most are triggered by a footfall exerted on a pressure plate. AP blast mines contain 30-250g of explosive. They rely on the shockwave to cause injury and form few fragments.

AP fragmentation mines (Figure 2.12b) are usually positioned above ground on stakes or concealed in vegetation and are tripwire-operated. AP fragmentation mines have 75-200g of explosive that propels fragments in a fan around a 360° arc. They are often fatal to unprotected personnel at 5-20m and inflict serious wounding at 10-30m. Area denial weapons such as the HB876 (Figure 6.13) are similar to AP fragmentation mines.

AP directional fragmentation (e.g. Claymore type) mines (Figure 2.12d) are hidden at the side of a route and are often initiated by a tripwire. They contain 200g-12kg of explosive that propels fragments over a fan of approximately 60° (rectangular type) or a narrow cone (cylindrical type). AP directional fragmentation mines are lethal to unprotected personnel in the firing line at 10-100m. Serious wounding is common at 30-200m. Larger mines are also effective against lightly armoured vehicles.

a b

c d

Figures 2.12a, b, c &d: AP landmines: (a) Russian PMN (blast), (b) Russian POMZ-2 (fragmentation), (c) Yugoslavian PROM-1 (bounding fragmentation), and (d) US M18A1 'Claymore' (directional fragmentation)

AP bounding fragmentation mines (Figure 2.12c) are buried and frequently tripwire-operated, although some are pressure or electrical command initiated. Each mine has two charges with a total weight of 100-500g. The first propels the mine into the air, typically 0.5-1.5m. The second explodes the mine, projecting a fan of fragments around a 360° arc. This gives a lethal range of 10-30m to unprotected personnel. Consistently serious wounds are inflicted at a 20-100m radius.

AT mines exhibit similar features as AP mines but are larger with an explosive weight of up to around 10kg, greater complexity of arming and anti-tampering devices. AT blast and shaped-charge mines are positioned under a route. The former may have several mines stacked together to increase the explosive power. The latter forms a vertical jet of metal that can easily penetrate 40-140mm of conventional tank belly armour. Off-route AT mines are also available that fire an explosive round that detonates on impact with the target. Others explode to forge a single, dense, high velocity fragment. AT mines usually contain a high metal content so are frequently destroyed or disrupted by hand.

UXO are conventional military weapons such as bombs (Figure 2.13), shells (Figure 6.18), mortars, grenades (Figures 6.9 & 6.12) and sub-munitions (Figure 6.15) that have not detonated. These too may range from a few grams of plastic explosive in hand grenades to hundreds of kilograms in aerial bombs, e.g. 240kg of Tritonal in a UK Paveway III (Hewson & Lennox, 2004). They also have associated blast, fragmentation, incendiary and anti-tampering characteristics. One feature that UXO exhibit, in common with landmines, is a likelihood of being found in a state that they were not designed for. For example, grenades can have seized arming mechanisms; shells and mortars may be lying on their sides; bombs are sometimes buried metres deep in mud; AP blast mines may have been laid too deeply by untrained soldiers. This can make them less efficient weapons because e.g. fragments are not distributed as they have been designed to. However weathering, damage and timer fuses can make them a less predictable threat than standard ordnance.

Figure 2.13: Unexploded aerial bomb in Angola (Ehlers, 2004)

IEDs include terrorist bombs and booby traps, which can have non-standard components or constructions. They range in size from a few grams of explosive in letter bombs to tonnes of homemade fertiliser-based explosives in vans. For example, the largest homemade device encountered in Northern Ireland by 1991 was around 3,500kg (Birchall, 1997). A common scenario is that of the car bomb, set to trigger on ignition of the vehicle engine (Figure 2.14).

Figure 2.14: Demonstration of Mk 4 and Mk 5 EOD Suit ergonomics during the inspection of a vehicle (courtesy of NP Aerospace, Coventry, UK)

Threats can be grouped roughly by the efforts required to search for and then dispose of them. The search phase is generally longest for landmines and shortest for IEDs because the former are concealed *area* denial weapons, while the latter is often a *point* effect weapon that is reported by the public or non-EOD specialist. UXO varies between these two extremes. The effort to dispose of them depends on factors such as their stability, size, location and novelty.

2.3.2 Humanitarian demining

Landmines affect at least 90 countries in the world (ICBL, 2001). Each has its own context for mine action. Humanitarian demining is the clearance of land after the cessation of conflict. It is often carried out by charities and non-governmental organisations (NGOs). Humanitarian demining is a high quality, slow, low cost per explosive device type of EOD.

The physical side of humanitarian demining starts with desirable land that is suspected of being contaminated by mines or UXO. It finishes when the area has been “accepted as ‘cleared’ when the demining organisation has ensured the removal and/or destruction of *all* mine and UXO hazards from the specified area to the specified depth." (United Nations, 2003) This IMAS standard goes on to say that the target depth is "normally not less that 130mm below the original surface level… Shifting sands in desert areas or coastal areas may require clearance to a depth of 1.0m or 2.0m to locate and destroy mines which were originally laid at a depth of no more than 10cm." Several stages are required to clear to this standard. These can be broadly divided into surveying, area reduction, detection, clearance and quality control. A detailed introduction to humanitarian demining is available from the University of Western Australia (Trevelyan, 2000a).

Surveying is carried out to define the location and nature (e.g. threat type) of a suspected minefield. This information is recorded in order to assess the costs and benefits of clearing a particular area. An armoured mine clearance vehicle can be used at this stage for area reduction. An alternative approach is to use teams of dogs and handlers on foot to find the edge of a minefield (Figure 2.15). Trained dogs use their sense of smell to detect the presence of explosive then alert their handlers

Figure 2.15: Deminer in Bosnia using a dog to survey the edge of a minefield while standing in a cleared lane (Trevelyan, 2000a)

Detection and clearance include surface preparation. For example, vegetation can be removed mechanically by cutting (Figure 2.16), burning or with chemicals. In urban areas rubble may need to be sifted before mines and UXO can be accessed.

Figure 2.16: Deminer in Bosnia clearing vegetation and squatting behind a marker that designates the cleared end of his lane (Trevelyan, 2000a)

The manual detection and clearance processes typically involve teams of two people progressing slowly up a 1m wide lane (Figure 2.16) with a safety gap of around 50m to the next team. Each metallic fragment is located with a metal detector and then carefully excavated with a bayonet or prodder (Figure 2.17). Mines are commonly deflagrated or detonated in situ, unless they are in close proximity to vulnerable people. This process is slow but thorough, and can be cheap in third world countries where wages are low. The major technical advantages of manual demining are the quality of clearance and the ability to deal with difficult terrain.

Mechanical demining such as with armoured flails, rollers or ploughs (Paterson, 2000) can be faster and less exposed than manual clearance in flat, rural locations. A lane width of several metres can be cleared relatively quickly. However, there is greater potential to miss mines if there is no detection process. In addition, a mine clearance vehicle is less able to cope with variations in terrain than a person, which increases the likelihood of bypassing mines.

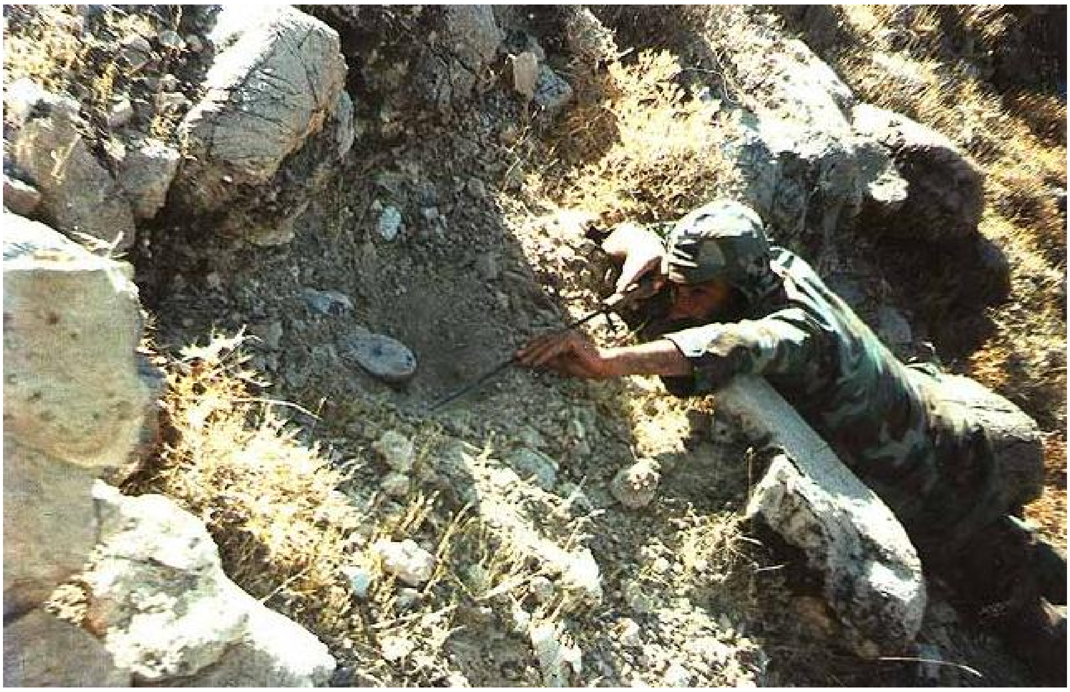

Figure 2.17: Deminer prodding around an AP blast mine in mountainous terrain in Afghanistan (Trevelyan, 2000a)

Quality control is the final technical process in mine clearance. Minefields must not only be cleared but also they must be shown to be clear. The author has received anecdotes of a humanitarian demining team holding a soccer match on a cleared area of land to prove its safety to the local population.

2.3.3 Combat EOD

The Royal Engineers (RE) take the lead in wartime EOD for the UK, except for certain specialities of the Royal Air Force (RAF) and Royal Navy (RN) (Birchall, 1997).

Military EOD during combat differs from humanitarian demining in the urgency of a conflict compared to peacetime scenario coupled with greater resources. The threat of greater casualties through inaction – e.g. due to sniper fire or airfield denial reducing air cover – means that military commanders need to accept a lower quality and higher cost of clearance in return for a greater speed. This is particularly true during high tempo fighting when EOD to maintain mobility of forces comes under the name of *countermine* operations. Minefield *breeching* tools such as Python (King & King, 2004b) – a hose fired across a minefield, filled with explosive and then detonated – focus on the clearance rather than detection aspect of demining.

NATO is cited (Birchall, 1997) as classifying EOD incidents according to the following categories. This helps the designer appreciate the levels of acceptable risk that military commanders are willing to take for different scenarios.

A. “Assigned to EOD incidents that constitute a grave and immediate threat. Category A incidents are to be given priority over all other incidents, and disposal operations are to be started immediately regardless of personal risk.”

B. “Assigned to EOD incidents that constitute an indirect threat. Before beginning EOD operations, a safe waiting period may be observed to reduce the hazard to EOD personnel.”

C. “Assigned to EOD incidents that constitute little threat. These incidents will normally be dealt with by EOD personnel after Category A and B incidents, as the situation permits, and with minimum hazard to personnel.”

D. “Assigned to EOD incidents that constitute no threat at present.”

During wartime, high priority areas are airfields, bases and supply routes. As the operational tempo slows during peacekeeping activities there is more time to assess the risk of EOD but the threat of further attack is not absent. Although the EOD threat may be similar to humanitarian demining the context is not; different personal armour solutions are required. Humanitarian demining armour thus needs to be cheap and comfortable; wartime military armour needs to allow swift action. Trevelyan (2000b) states the following differences between military countermine operations and humanitarian demining (Table 2.1).

Military Countermine Operations	**Humanitarian Demining**
High cost accepted (billions of $)	Low budget (millions of $)
Rapid response in short time	Continuous full-time work for years or decades
Highly trained personnel	Deminers have little or no formal education
Try to detect and avoid mined areas	Need to clear mined areas
New high tech surface laid mines are [a] threat	Nearly all are older style buried mines

Table 2.1: Differences between military countermine operations and humanitarian demining (Trevelyan, 2000b)

Combat EOD may take place anywhere in the world at any time so equipment must take into account the variation in environmental conditions. Figure 2.18 shows an EOD operator who has raised his visor during work, possibly because of the heat and dust of his surroundings.

Figure 2.18: Disposing of an unexploded mortar on Operation Fingal in Afghanistan (MOD, 2004)

EOD operators do approach devices in order to survey or work on them (Figure 2.18). They also use a variety of equipment at greater ranges such as the hook and line in Figure 2.19 which is used to move objects from a distance.

Figure 2.19: Using a hook and line on Operation Fingal in Afghanistan (MOD, 2004)

2.3.4 UK mainland EOD

EOD in the UK during 'peacetime' is usually either the result of past conflicts or terrorist activity. The RE are broadly responsible in the UK for conventional devices such as aerial bombs left over from e.g. WWII (Birchall, 1997). These may be metres deep in the ground or be located below significant buildings, so require skilled excavation (Figure 2.20) mechanically or by hand.

Figure 2.20: A Royal Engineer defuses a WWII bomb in Sunderland, UK after access has been excavated (MOD, 2002)

Terrorist IEDs are largely the domain of the part of the Royal Logistics Corps (RLC) that was formerly the Royal Army Ordnance Corps (RAOC). Improvised Explosive Device Disposal (IEDD) includes the activities of other EOD operations. The area is defined and cordoned off; a search pattern is conducted to locate devices; they are identified and recorded; the disposal task is prioritised; then disposal can be carried out. A remote controlled device named the Wheelbarrow (Figure 2.21) allows EOD personnel to carry out many tasks at a safe distance. It carries cameras for observation along with tools to dispose of threats. However, not all scenarios are applicable to the use of remote working. The Bomb Disposal Officer (BDO) must then approach the device in person. His 'Number 2' helps him don an EOD Suit such as the MedEng suit in Figure 2.22. He then makes the 'longest walk' alone. The disposal task may include preparing shielding such as sandbags, moving surrounding objects or the ordnance itself using a hook and line (2.19), setting up equipment and withdrawing to a safe distance from which to work.

Figure 2.21: Remotely controlled EOD 'wheelbarrow' (King & King, 2004a)

A typical piece of equipment that a BDO will carry forward is a disrupter, nicknamed a 'Pigstick' (Figure 2.22). It fires a blast of water or gel at the IED in order to separate the fuse from the main charge before it can detonate. Disarmers are also used that fire a chisel or metal bolt to achieve a similar effect. The total weight of a Pigstick is around 4kg (King & King, 2004a).

Figure 2.22: Training to disrupt an IED using a 'pigstick' (King & King, 2004a)

2.4 A BRIEF INTRODUCTION TO SYSTEMS CONCEPTS

2.4.1 Systemic thinking as the cradle of systems theory

Systemic thinking is not new. Plato used it in the Western world around 400 BC in an attempt to improve society. In “The Republic” (Plato, 360 BC), he starts with Socrates’ elicitation of justice that covers individual and group morality. This may be seen as drawing out a central objective of society. He continues to analyse patterns of society advocating a top-down approach, “‘Let us suppose we are rather short-sighted men and are set to read some small letters at a distance; one of us then discovers the same letters elsewhere on a larger scale: won’t it be a godsend to read the larger letters first and then compare them with the smaller, to see if they are the same?’” Socrates finds two cohesive influences for a society to form that counteract the dispersive nature of such individual traits as greed. The first being mutual need as expressed in “‘Society originates, then,’ said I ‘so far as I can see, because the individual is not self-sufficient, but has many needs he can’t supply himself.’” The second is the difference in aptitude of people, of the need to differentiate the functions of society into specialised groupings. Plato identifies that a system is made up of individual parts that come together to achieve synergy: People trade their efforts for common benefits. He then goes on to discuss the manipulation of the system through education and politics to produce a philosopher ruler to achieve his central objective of a just society.

Around the same era, Sun Tzu used systemic thinking to win wars in the East. “The Art of War” (Sun Tzu, 4th C. BC) still has relevance for military and, through analogy, commercial thinkers today. One of the most important passages is “Victory is the main object in war. If this is long delayed, weapons are blunted and morale depressed.” This is further clarified by stating that the best sort of win is one where no fighting takes place, since war only destroys resources or spoils. Thus, the central objective of war is laid down: win, as fast as possible and with as little bloodshed as possible. To do this, he analyses factors such as moral influence, weather, terrain, command and doctrine and draws out key ‘truths’ on the art of warfare. He advocates the gathering of knowledge – even so far as using spies – and of mathematical modelling, “Now the elements of the art of war are first measurement of space; second, estimation of quantities; third, calculations; fourth, comparisons; and fifth, chances of victory.” Sun Tzu also exhibits a key systems engineering characteristic of responding to change with iterative thinking: “Of the five elements, none is always predominant; of the four seasons, none lasts forever; of the days, some are long and some are short, and the moon waxes and wanes. Therefore, when I have won a victory I do not repeat my tactics but respond to circumstances in an infinite variety of ways.”

Plato and Sun Tzu are two examples of classical philosophers that demonstrate systemic thinking. Systemic thinking allowed them to analyse a system so that truths could be obtained in order to make improvements; whether that be for a just society or to win wars. Part of their genius is that they, amongst others, not only examined specific systems of interest but also developed the foundations of *systems theory*. For example, Plato's Theory of Forms (Plato, 360 BC) – that everything has a higher pattern associated with it – is a cornerstone of systems thinking. In Plato's terminology one might say that systemic thinking means identifying a form and systems thinking means identifying a form of forms: a universal pattern.

2.4.2 Systems theory

General Systems Theory (GST) evolved to counter weaknesses in the reductionism of classical science; that of separate and disparate strands of knowledge. It was developed in the twentieth century by, in particular, von Bertalanffy (1955) and Boulding (1956) as cited by Skyttner (1996). GST is based on the assumption that there is a law of laws applicable all types of system regardless of whether they are man-made, natural, abstract, etc. It is therefore a metadiscipline that can be transferred across scientific disciplines. Cybernetics – the science of control founded by Wiener (1948) as cited by Skyttner (1996) – has supplemented the body of knowledge. Greater detail on systems theory is provided elsewhere (Checkland & Scholes, 1991, Hitchins, 1992, Skyttner, 1996). Summaries of a selection of the key concepts useful for this thesis are listed below.

1. *A system has interrelated and interdependent parts, components or elements* (Figure 2.23). The parts exhibit *order* and *pattern* or *structure* relative to each other. Inclusion or exclusion of an individual element affects others within the system. Element 5 is therefore not part of the system in Figure 2.23 because it is unconnected.

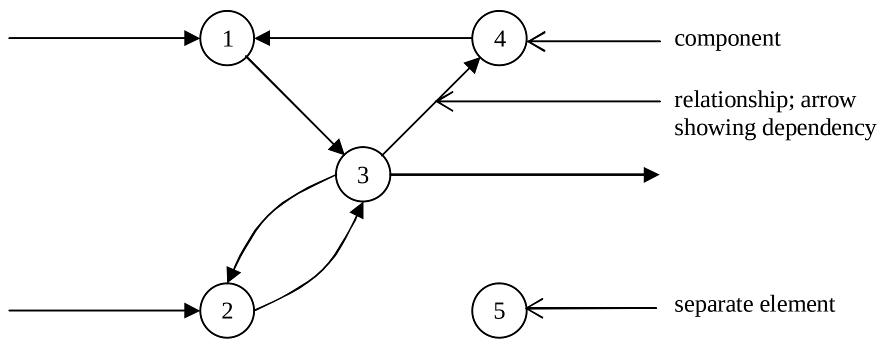

Figure 2.23: Interrelated and interdependent components exhibit order and structure

2. *Parts are unified into wholes, from which novel properties emerge.* The holistic paradigm implies that the "whole is greater than the sum of its parts," to introduce the idea of *synergy* that is part of the greater named *emergence*. This phrase is quoted frequently to describe synergy and is suggested (Shalen, 1994) to be a modification of Euclid's axioms (Casey, 1885) that "The whole is greater than its part," and "The whole is equal to the sum of all its parts." These two statements hold true for Euclid's subject of classical geometry but are single cases in systems theory, i.e. that of nil synergy.

3. *The system is contained within a boundary* (Figure 2.24). Exterior to the boundary is the *environment*. The boundary can be considered to have length, breadth and depth. 'Length' refers to the timescale over which the system is considered; 'breadth' appertains to the variety of components contained within the boundary; 'depth' concerns the level of detail to be assessed. In the analogy of using a microscope to study a system, length, breadth and depth equate to the duration of observation, field of view and resolution respectively. The boundary puts a limit on information gathering so that it is possible to comprehend the system.

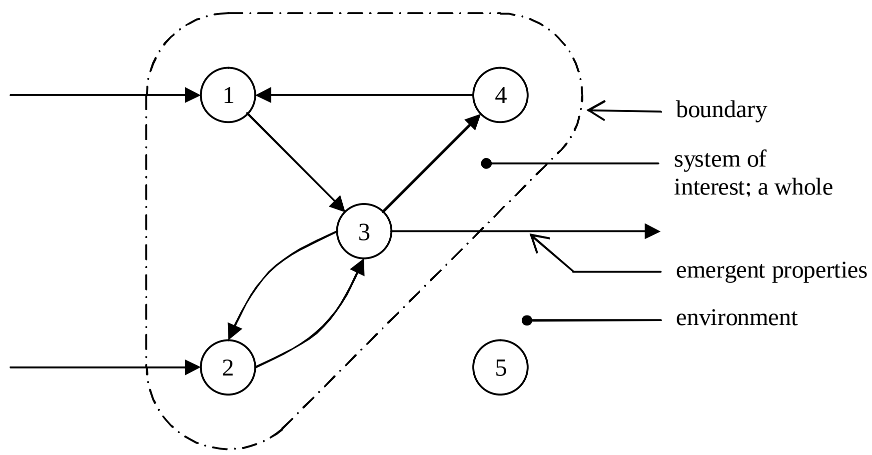

Figure 2.24: The boundary separates the system of interest from the environment

4. *A hierarchy of systems* is envisaged from the combination of elements into more complex wholes. Elements combine to form *subsystems*, which create systems that are contained with *suprasystems* (Figure 2.25). This concept is traced (Skyttner, 1996) back to Aristotle's (384-322 BC) metaphysical vision of the hierarchic order of nature. Emergent properties apply up the hierarchy to more complex levels but not down to simpler ones.

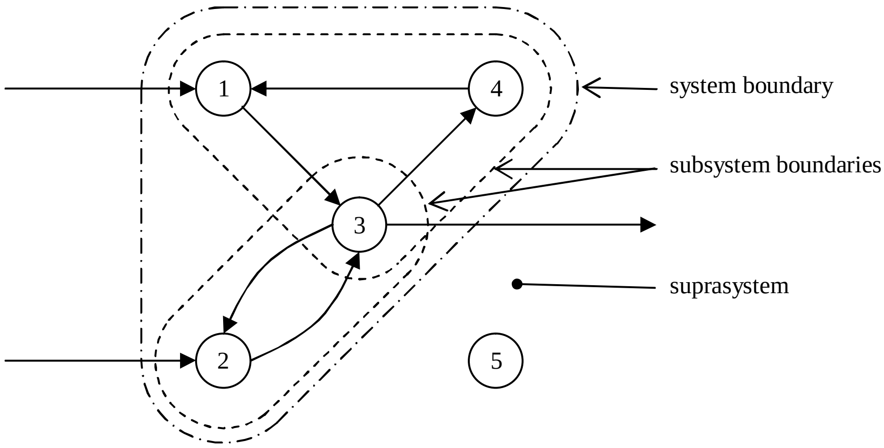

Figure 2.25: Subsystems are hierarchical divisions of a system

5. *Open systems have inputs and outputs that cross the boundary* (Figure 2.26). That is to say open systems are dependent upon and affect the environment. Completely *closed systems* have a locked boundary for which there is no input or output. There is a *transformation process* within the boundary that converts the inputs via *functions* to outputs. These concepts are founded in cybernetics.

Figure 2.26: Inputs are transformed by processes in the system into outputs (Skyttner, 1996)

6. *A system exhibits purpose* and aims towards a *goal*, *final state* or *equilibrium*. There may be single or multiple endpoints (Figures 2.28a & b). Churchman (1968) calls these *central objectives*. In the previous section, Plato's goal is to build a just society and Sun Tzu's is to win wars.

7. Some form of *regulation exists to focus the system on its purpose*. Cybernetics introduces the concepts of feedforward and feedback for *closed-loop systems* (Figures 2.27a & b). Feedforward is the mechanism by which future events are predicted and planned for: inputs influence outputs. This includes trials- and computer-based simulation for personal armour design, in order to predict casualties before they happen. Feedback is the mechanism by which the system reacts to events at a later stage: outputs influence inputs. If a weapon manufacturer increases the offensive threat, then the

armour designer may increase the defensive response. This in turn will encourage the weapon manufacturer to increase the offensive threat, hence starting another cycle of this feedback loop. Two important types of this mechanism are *negative feedback* and *positive feedback*. The former applies a negative fraction of the output to the input so as to reverse the direction of change towards a *stable* equilibrium (Figure 2.28a). The latter feeds a positively scaled version of the output back to the input. This causes the output to be *unstable* and speeds up change (Figure 2.28b).

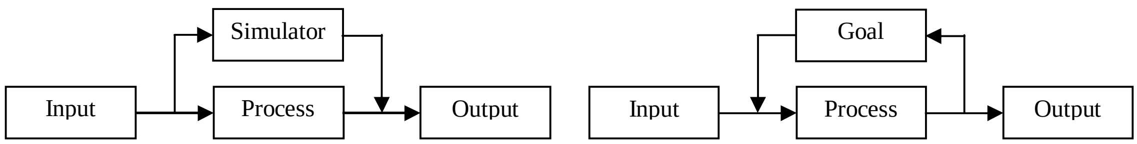

Figure 2.27a & b: (a) Feedforward and (b) feedback loops (Skyttner, 1996)

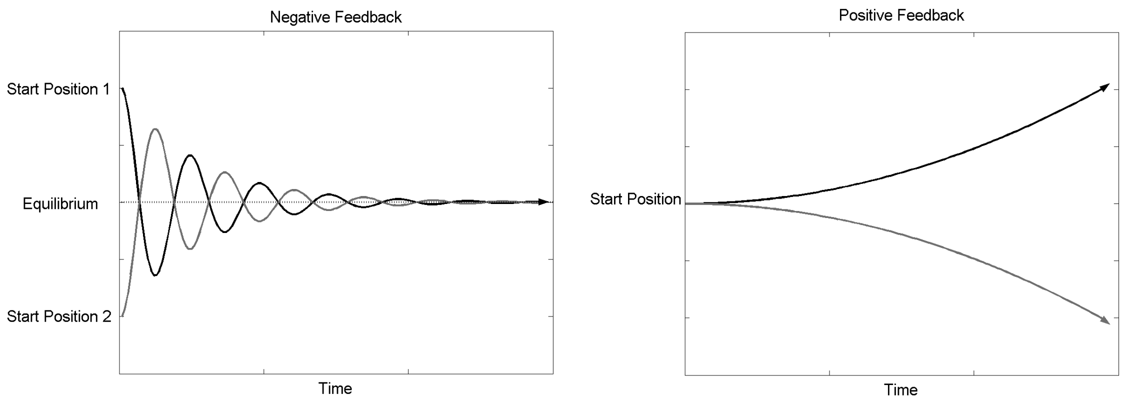

Figure 2.28a & b: (a) Negative feedback regulates towards a stable equilibrium while (b) positive feedback causes the output to be unstable and speeds up change (Skyttner, 1996)

8. *Open systems exhibit equifinality and multifinality*: they can achieve the same goals in alternative ways (*convergence*) and different, mutually exclusive ones from the same start conditions (*divergence*). Equifinality is demonstrated by equivalent protection being achieved by either covering a person in perfect armour or keeping them out of a danger zone. Multifinality occurs when an armoured person either lives or dies when put in the same situation due to the stochastic nature of the threat.

9. *Systems have both cohesive and dispersive influences* (Hitchins, 1992). These provide the benefits and penalties that must balance for a system to exist. The natural aversion to injury is a reason to design armour, while the constraints of wearing it prevent the attainment of absolute protection.

10. *Open systems exhibit entropy*: work must be done to maintain their viability. For example, armour is redesigned over the course of history in order to cope with weapons evolution. If garment designs were to stay the same then their worth as armour would cease to exist and no one would use them.

Concepts of systems theory such as those presented above provide a language for observing systems. *Systems engineering* goes beyond this; to manage the creation or manipulation of systems in order to achieve desired effects.

2.4.3 Systems engineering process

Systems engineering is cited (Buede, 2000) as being defined (Forsberg & Mooz, 1992) as "The application of the system analysis and design process and the integration and verification process to the logical sequence of the technical aspect of the project lifecycle." This is a process-driven definition that sidelines the creative side of systems engineering, such as deciding where to draw the boundary. Nevertheless, it does form the basis of Forsberg & Mooz's (1992) frequently quoted "Vee" model (Figure 2.29) that proposes how a system – rather than what – is engineered. This model uses the notion of hierarchy to decompose a concept from the *top, down* to designs and then construct the subsystems from the *bottom, up* to the whole system.

The "Vee" model starts with a system concept and the elicitation of *user or stakeholder requirements*. Different people have alternative perspectives on what a system should be and do. This idea is presented in Plato's Analogy of The Cave (Plato, 360 BC), whereby a man that lives solely in a cave and sees only shadows of the world outside has a very different picture of the Earth than a man who leaves the cave. In another example, the armour wearer may see his garment as a benefit because it offers protection, whereas the enemy may consider it to be a hindrance for the same reason. A systems engineer must reconcile these differences in order to elicit the desired emergent properties.

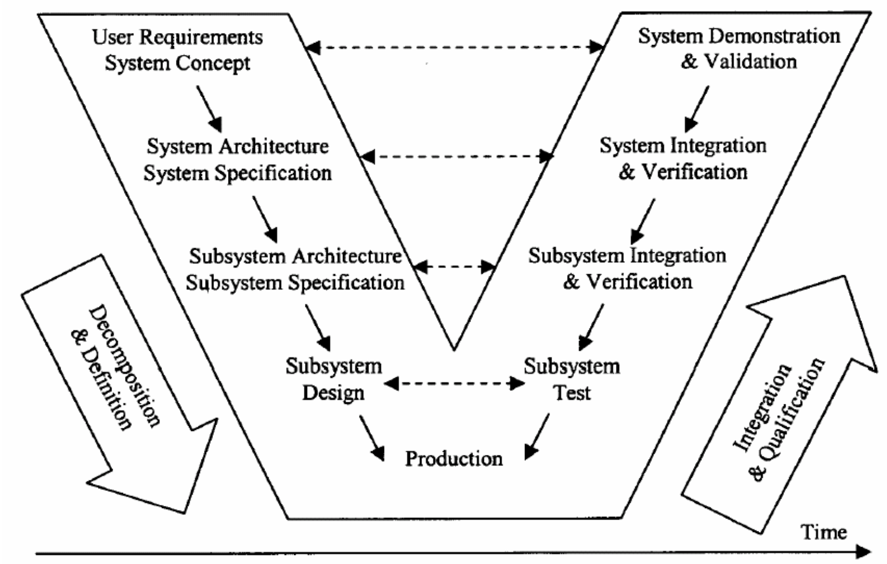

Figure 2.29: Systems engineering "vee" model (after Forsberg & Mooz, 1992)

The system concept provides the possible components and inputs, while the user requirements define the desired emergent properties or outputs. The engineer then specifies the *architecture* or pattern of parts and relationships, and the subsystem performance characteristics that are predicted to achieve the user requirements best. Thus, requirements flow down to the architectural decisions of the lower system levels.

The system is decomposed until it is believed to be understood sufficiently within the constraints of available resources such as time and money. Components are first integrated into subsystems and then into systems. At each system level, the predictions of the decomposition phase are *verified* through comparison with the results of the integration stage. Finally, the completed system is *validated* by demonstrating it against the original requirements.

2.5 CONCLUSIONS

1. Non-EOD personal armour includes 'bullet-proof' jackets, stab-resistant vests and riot shields. These are not used for EOD because they are designed for a significantly different context. Their similarities and differences with EOD personal armour are used in Chapter 5 to help validate the elicited system.

2. General purpose armour that is used for EOD includes fragmentation vests and combat helmets. These offer a degree of protection over the torso and head from AP fragments and allow a greater freedom of movement than full suits. This is the lightest EOD armour ensemble at around 5 to 7kg for ECBA with a GS Mk 6 helmet and a polycarbonate visor.

3. Current EOD-specific personal armour includes mediumweight (around 15 to 20kg) and heavyweight (around 25 to 30kg) EOD suits. The former are used where fragmentation is considered to be the greatest threat and mobility has a high priority, such as during combat EOD. The latter are employed for more or less predictable threats when mobility has a medium priority, e.g. during disposal of terrorist bombs.

4. The current, conventional, land-based EOD threat is from landmines, UXO and IEDs. These range in size from tens of grams to hundreds of kilograms of explosive. They have a variety of frequencies, methods and distributions of attack. The threats can be grouped roughly by the efforts required to search for and dispose of them.

5. Humanitarian demining occurs after the cessation of conflict, usually by NGOs. It involves surveying, area reduction, detection, clearance and quality control. All stages can require people on the ground using tools such as trained dogs, scrub cutters, metal detectors, prodders and explosives. Humanitarian demining is a slow, high quality, low cost per explosive device type of EOD. The emphasis is on clearing 100% of threats from desirable land.

6. Combat EOD is a faster, lower quality, higher cost per explosive device type of EOD that takes place during war fighting and subsequent peacekeeping operations. The goal is to promote mobility of military forces and access to key sites such as airfields and roads. There is an additional threat from further attack by e.g. snipers.

7. EOD on the UK mainland is usually of UXO from past conflicts such as WWII or terrorist's IEDs. Devices tend to be reported by the public or non-EOD specialists so require less effort to find than humanitarian demining. IEDs in particular can have novel constructions, variable stability and close proximity to vulnerable people.

8. Systemic thinking is a mode of reasoning that allows a person to balance a variety of factors for the improvement of a specified system. It has been used by philosophers since at least the era of classical history. The greatest philosophers of this time provide the foundations to what has become systems theory.

9. Systems theory is the metadiscipline that is an abstraction of systemic thinking. Concepts such as emergence, boundary and hierarchy provide a language to describe all systems whether real or abstract, natural or man-made.

10. Systems engineering is the utilisation of systems theory to construct or manipulate systems for a specified purpose. Some writers have ignored the creative side of systems engineering such as deciding where to draw the boundary: missing the question, "What system shall be engineered?" Nevertheless, systems engineering process helps answer the question of "How a system can be developed?" The commonly quoted "Vee" model is an example of a system being analysed from the top-down before it is constructed from the bottom-up. At each system level, the predictions from the analysis phase are compared with those of the synthesis.

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CHAPTER 3: STATE OF THE ART IN RELEVANT PERSONAL ARMOUR DESIGN TOPICS

3.1 INTRODUCTION

3.1.1 Aim

To present the current state of the art in topics which provide the foundations for this research.

3.1.2 Objectives

- Present a critical review of relevant personal armour design literature,
- Present the appropriate breadth or depth of information for each topic,
- Leave descriptions of other literature until the relevant chapters of this thesis.

3.1.3 Background

This literature review demonstrates the knowledge upon which this research is founded. It is not a complete documentation of all subjects related to personal armour design but is focussed on ideas that support this thesis.

The multiple system levels considered in this work require different degrees of scope and resolution. For example, topics that support the system level of Chapter 5 are included for their breadth rather than their depth. The opposite is true for the subjects that support the sub-subsystem level of Chapter 7. It is therefore appropriate that some topics are presented in more detail than others.

3.2 THREAT EVALUATION

3.2.1 Ballistic threats

Ballistic threats can be divided roughly into two categories: bullets and fragments. Examples of the former are supplied in police ballistic vest proof tests (NIJ, 2001, Croft, 2003). These are single – though several shots can be fired in succession – projectiles that have consistent initial properties. Low velocity bullets are fired from handguns at short ranges. High velocity rounds are fired with rifles such as the ubiquitous AK47 and are more often associated with military scenarios.

Fragments, in contrast with bullets, can have a range of shapes, sizes, stabilities and velocities depending upon their formation and so are stochastic in nature. They can be divided roughly into 'battlefield', high-energy and secondary fragmentation. 'Battlefield' fragments are designed to be produced by conventional antipersonnel (AP) munitions. For example, the UN (2001) dictates that personal armour for use by their humanitarian deminers should be tested against 1.102g chisel-nosed fragments simulating projectiles (FSPs) (NATO, 1996) with a velocity of 450ms^{-1}. These angular, experimental projectiles are a relatively repeatable approximation of irregular fragments formed from the casing of disintegrating munitions. However, they are relatively expensive to produce and may be of questionable realism. An alternative is to use preformed fragments such as spherical steel balls which are used within many AP munitions.

High-energy fragments are produced when conventional AP munitions break in to large pieces or detonate at close range. For example, a grenade is designed to form many 'battlefield' fragments but the fusing assembly may stay intact. Improvised explosive devices (IEDs) and anti-armour weapons may also produce high energy fragmentation by design. Calver (1995) compares properties of 'battlefield' and high energy fragments with low and high velocity bullets (Table 3.1).

Projectile	Mass / g	Velocity / ms^{-1}	Energy / J
'Battlefield' fragment	0.2	600	36
'Battlefield' fragment	1.0	500	125
LV bullet – 9mm 2Z	8	360	518
LV bullet – 0.357" magnum	10	430	925
HV bullet – L2A2 5.56mm ball round	3.9	970	1,835
HV bullet – L1A1 7.62mm ball round	9.0	840	3,175
High velocity (& high energy) frag.	1.0	1800	1,620
High velocity (& high energy) frag.	5.0	1500	5,625
High velocity (& high energy) frag.	50.0	1200	36,000

Table 3.1: Comparison of 'battlefield' and high energy fragmentation with low and high velocity bullets

Secondary fragmentation comes from the material surrounding, but not part of, an explosive device. Beyer (1962) defines a secondary missile as "a missile which has been set into motion by another or primary missile and which has travelled an appreciable distance in the air or other mediums before causing a casualty." Work on unconstrained secondary fragmentation is cited (Baker et al., 1983) and carried out by Valasis (2003) as well as citation of work on constrained material (Westine, 1977). These provide analytical models for the assessment of unconstrained and constrained secondary fragmentation that is close to the charge – where the initial velocity is purely a function of the imparted impulse.

One example of secondary fragmentation occurs if a buried landmine detonates: stones in the earth become ballistic threats as well as pieces of the casing. The resultant cratering at various depths of burial (DOB) is categorised (Defense Nuclear Agency, 1979) as cited by Cooper (1996) and shown in Figure 3.1. Photographs are presented (Braid et al., 2004) that illustrate the effect of cratering on the distribution of ejected material for 200g of C4 at a DOB of 20mm (Figures 3.2a & b: overleaf). The threat of secondary fragmentation is assessed by DCTA (Gotts, 1999b) for the development of the Lightweight Combat EOD Suit during arena trials. This provides the data gathering opportunity for Chapter 7.

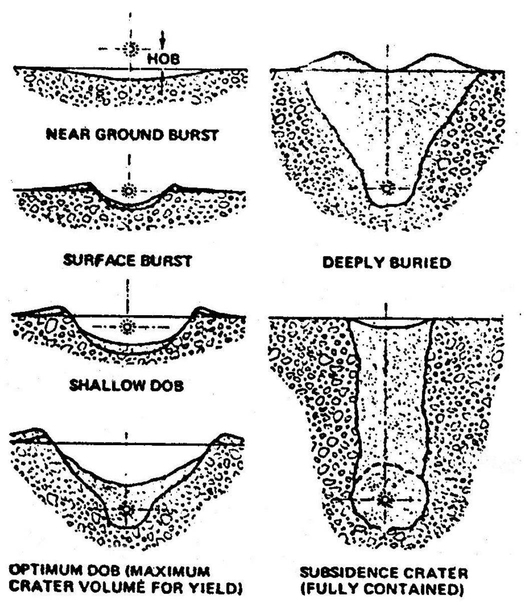
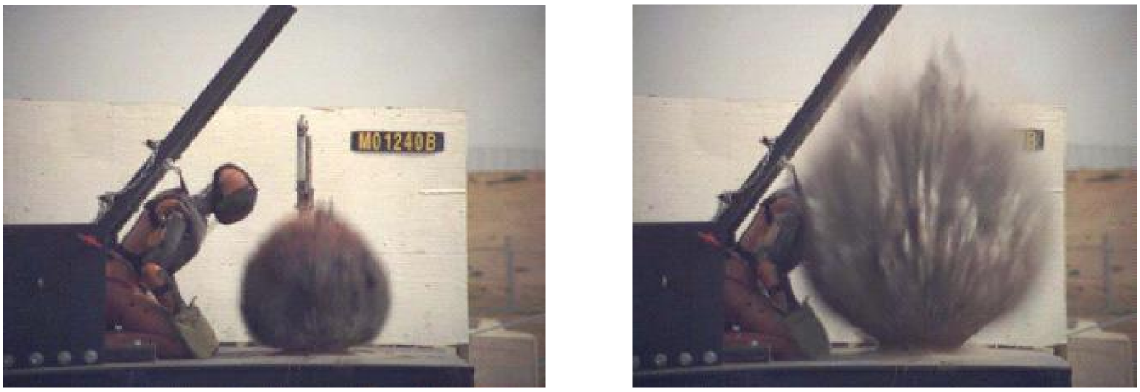


Figure 3.1: Craters formed by the displacement of secondary fragmentation

Arena trials are the main method used to obtain experimental measurements of fragment distributions from threats (Beyer, 1962, Dmitrieff, 1984). A munition is surrounded by targets at known ranges and then detonated. Fragments are caught in the targets, which are recorded for their mass, position and estimated velocity. Strawboard (British Defence Standards, 1997) is a common choice of target in the UK and is used in the DCTA trials (Gotts, 1999b). It is used in packs of multiple layers so that the depths of fragment penetration can be observed and is calibrated for metallic fragments (McMahon, 1971). The results of 'battlefield' fragmentation arena trials are the primary source of threat data for casualty reduction analysis tools such as CASPER (Hunting Engineering, 1999) (Section 3.5.1).



Figures 3.2a & b: The distribution of matter ejected from the crater formed by 200g of C4 buried to a depth of 20mm at a time after detonation of (a) 1ms and (b) 2ms (Braid et al., 2004)

3.2.2 Blast threats

The threat during the explosion of ordnance is not limited to fragmentation. A pressure shock radiates out from the point of detonation in the form of a blast wave that approximates the ideal pressure-time history (Kinney & Graham, 1985). The overpressure phase is characterised by the arrival of the shock front, causing a rapid (<1μs) increase in pressure that declines to atmospheric pressure, P_a (overpressure phase). Gases from the explosion continue to expand outwards, reducing the pressure below P_a. The pressure is equalised when air flows back into the void (underpressure phase). Three factors are used to describe this blast wave: a measure of the shock intensity such as peak pressure, P_s, compared to P_a; the duration of the overpressure phase; and a measure of the wave shape such as the impulse per unit area.

Airblasts occur away from any surfaces so that the wave expands equally in all directions. Most EOD work occurs while the device is on or near the ground. Reflection of the blast wave increases the energy transmitted towards an observer. This depends on the geometry and the physical properties of the reflecting surfaces. An unimpeded ground burst expands as a hemisphere this increases the blast threat at a given range compared to pure airblasts because the same energy is focussed over half the surface area. If the ground is assumed to be a perfect, infinite, plane reflector then a surface burst will appear to have the properties of an airburst with 2 times the explosive energy. It is reported (Smith & Hetherington, 1994) that, in practice, good correlation for hemispherical surface bursts with airburst data results if an enhancement factor of 1.8 is assumed, due energy being dissipated in producing a crater and groundshock. Kingery and Bulmash (1984) are cited (Smith & Hetherington, 1994) as presenting blast parameter versus distance for a 1kg TNT hemispherical Surface Burst (Figure 3.3).

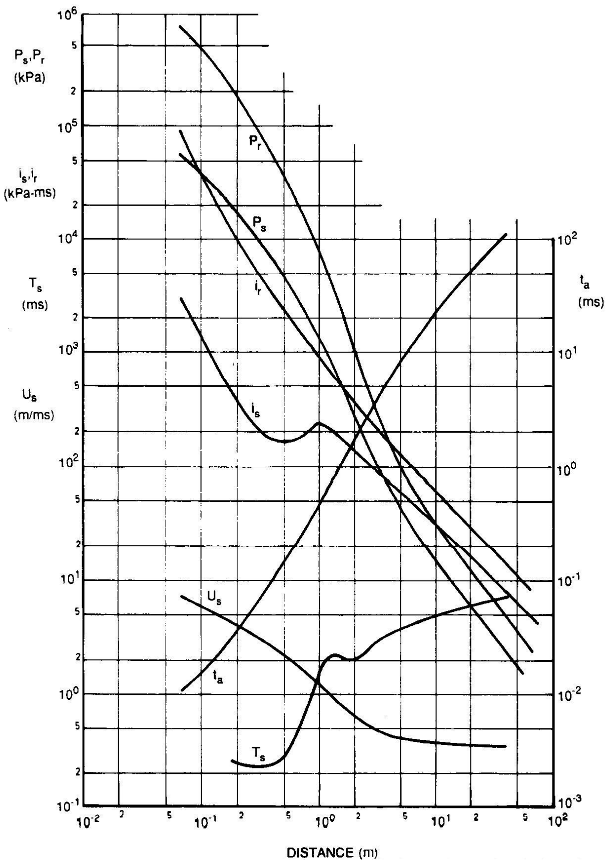


Figure 3.3: Blast wave parameters versus distance for 1kg TNT hemispherical surface burst (Kingery & Bulmash, 1984)

It is possible to scale up or down the data in Figure 3.3 for different charge sizes. Hopkinson-Cranz scaling (Hopkinson, 1915, Cranz, 1926) is cited (Smith & Hetherington, 1994) as the most widely used approach to blast scaling. Equation 3.1 relates the ranges, r_1 and r_2, of two charge masses, m_1 and m_2, at which a given overpressure is achieved.

$$r_1 = r_2 \left(\frac{m_1}{m_2}\right)^{1/3} \tag{3.1}$$

Most conventional munitions such as shells, fragmentation grenades and mortars use explosive energy, primarily, as a mechanism to propel ballistic projectiles. Others use point source blast energy as a principal method of attack when the device (e.g. AP or AT blast mines, and some IEDs) detonates. These require the explosive to be close to the target because the destructive potential of blast (e.g. peak overpressure) decays rapidly with range (Figure 3.3) when compared to fragmentation. Newer, thermobaric threats have been reported to be in use in Chechnya (Haydar, 2000) and man-portable versions for the RPG-7 rocket-propelled grenade launcher are available on the world market (Foss, 2004). These use an initial charge to spread explosive fuel in a cloud, which is then detonated by a secondary charge. This causes the blast's destructive potential to be greater at longer ranges than are possible with equivalent, conventional point-source explosions (Figure 3.4).

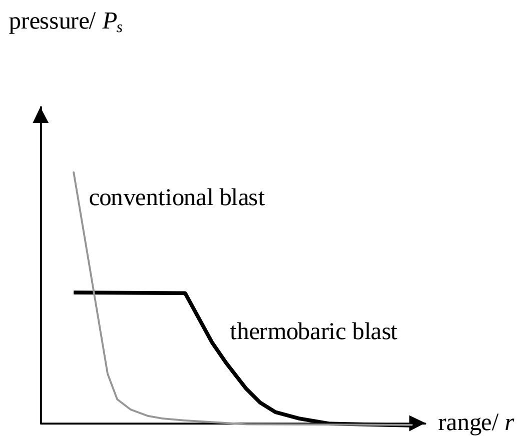


Figure 3.4: Comparison of conventional and thermobaric blast overpressure decay (after Haydar, 2000)

3.2.3 Thermal threats

Calver (1995) states that thermal energy is the third threat from an explosive device, after fragments and the blast wave. More specifically, it is the conductive heat flux from being immersed in flame rather than radiant energy that is considered to be the cause for concern. This threat can be divided into two parts: flash and flame. Flash is the initial fireball resulting from the ignition of flammable gases and is characterised as very hot for a short duration. Reference tables are available (Kinney & Graham, 1985) that give the temperature and duration of shock waves in dry air at 15ºC and standard P_a of 101.325 kPa.

Flame is the immersion in a hot environment for a longer period of time. For example, fire-fighters' clothing is tested (BSI, 1992, 1993) against a thermal flux of 80 kWm^{-2}. Flame is particularly important for incendiary devices.

3.2.4 Relative likelihood of threat types

The relative likelihood of personnel being faced with particular threat types must be considered by the personal armour designer. For example, both bullets and fragments may be a potential threat to EOD personnel. Their relative frequency can be estimated from casualty data, however this is vulnerable to change. Fragmentation was the main source of combat incapacitation during the much of the 20th Century. In a survey of 7,773 wounds in 4,600 WIA US casualties during the Korean War in November 1950, more than 84% were due to fragments (Beyer, 1962). It is reported (Lovric et al., 1997) that "during 18 months of the 1991/92 war against Croatia, 4,545 injured were treated… Some 2,544 (55.9%) sustained shell fragment injuries and 807 (17.8%) bullet injuries. The trend of an increasing proportion of bullet wounds was discussed in a report of casualties in Chechnya in 2000 (Titius, 2002). For example, Titius concludes that a high number of head injuries reflect a more frequent encounter with snipers. It is envisaged (Tonkins, 2000) that the current threat to combat EOD operators of the Royal Engineers is comprises of a majority of explosive hazards (fragmentation and blast) with a lesser threat from bullets (Figure 3.5).

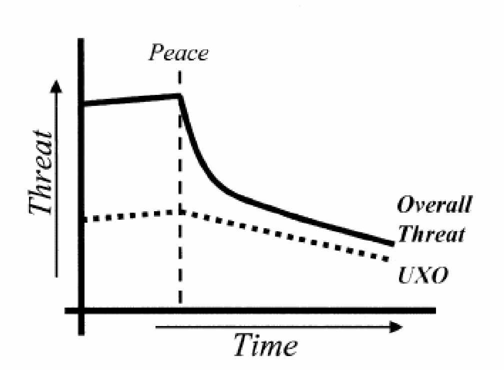


Figure 3.5: Relative likelihood of threat types for Royal Engineer EOD personnel during and after combat operations (Tonkins, 2000)

Verhagen (2002) uses the probability of occurrence, $P_{occurrence}$, of a particular threat combined with the likely severity of effect to rank the risks posed to an armour wearer.

3.3 ESTIMATION OF ARMOUR RESISTANCE TO THREATS

3.3.1 Resistance to ballistic threats

Armour's ability to resist ballistic threats is a function of its constituent materials and geometry compared to the threat and wearer. Materials absorb a threat's destructive potential. The state of the art in resisting ballistic energy and momentum is to use soft armours for 'battlefield' fragmentation and low velocity bullets, and hard armours for high energy fragmentation and bullets. Current soft armour materials include para-aramids such as Kevlar® (DuPont, 2003) and Twaron® (Teijin Twaron, 2004), and ultra-high molecular weight polyethylene (UHMWPE) e.g. Dyneema® (DSM, 2004) and Spectra® (Honeywell, 2004). Hard armours in current usage tend to be composite-backed aluminium oxide (Al_2O_3) (Morgan Advanced Ceramics, 2004) but other ceramics such as silicon carbide (SiC), boron carbide (B_4C) and titanium diboride (TiB_2) are available. Other materials in use include transparent materials such as glass and polycarbonate (PC) e.g. Lexan® (GE Plastics, 2004).

The ability of armour material to resist perforation by ballistic threats is assessed in proof tests (NIJ, 2001, Croft, 2003). These are simple go-no go tests to prove that a garment will defeat a threat of stated initial properties. However, the likelihood that a projectile perforates armour, $P_{perforation}$, is stochastic rather than deterministic. STANAG 2920 (NATO, 1996) is a crude method of deducing an approximate V_{50} (the velocity at which it expected that 50 percent of identical projectiles will perforate the material: $P_{perforation}$ = 0.5). At least six identical projectiles are fired at a target. Propellant is added or removed to provide a spread of velocities within specified limits; some of which perforate the target and some of which do not. V_{50} is calculated as the mean velocity of the three highest perforations and three lowest non-perforations. More refined analysis techniques that use perforation versus non-perforation data are available (Kneubuehl, 1996, Tobin, 1998, Gotts et al., 2004). These estimate a V_0 (the velocity at which it expected that 0 percent of identical projectiles will perforate the material: $P_{perforation}$ = 0) in addition to a V_{50}.

Techniques have been proposed that use the residual properties of projectiles after perforation (Tobin, 1998). Tobin uses the assumption that the energy lost from a given projectile that perforates a particular target is constant and independent of the strike velocity, V_s. This is a reasonable approximation for soft ballistic armours and non-deforming projectiles. It means that the residual velocity of the projectile after perforation, V_r, is given by Equation 3.2. V_L is used in this thesis to denote the limit velocity at which a single projectile will perforate a target.

Tobin suggests that substituting V_0 instead of V_L in Equation 3.2 provides a reasonable fit to experimental data allowing V_0 to be estimated.

$$V_r^2 = V_s^2 - V_L^2 \quad \text{on the condition that} \quad V_s > V_L \tag{3.2}$$

The casualty reduction analysis program named CASPER (Hunting Engineering, 1999) (Section 3.5.1) has an option to model projectile-target interaction materials' by using Equation 3.2 in the opposite sense to Tobin. Rather than estimate the velocity at which a projectile has a 0% chance of perforating a target; a value of V_L is assigned to an armour material to calculate V_r when V_s is known.

The assumption of constant energy loss is also the basis of kinetic energy density, *KED* – the kinetic energy of a projectile divided by its impacting cross-section area – as a predictor of ballistic perforation.

Investigation (Hetherington, 1996), that follows debate (Shu & Hetherington, 1992), demonstrates that neither energy nor momentum lost from a projectile that perforates a particular target are truly independent of V_s. Hetherington concludes from a combination of analysis from first principles, established penetration (projectile enters target) prediction equations and experimental data that "It is unsafe to assume that the energy or momentum transferred from a bullet during ballistic perforation is equal to that transferred in the 'just stopped' condition." Equation 3.2 and *KED* are therefore approximations of reality that are acceptable for soft armour-'battlefield' fragmentation interaction but are not universally applicable.

The geometry of armour influences resistance by deflecting threats and covering a sufficient area of the wearer. It is well known that armours can cause projectiles to ricochet (Sellier & Kneubuehl, 1994) at certain angles of incidence or obliquity, β – the angle between a projectile trajectory and target plane. Ballistic proof tests (Croft, 2003) (NIJ, 2001) cater for impacts for which $0^\circ < \beta < 30^\circ$. Research (Tobin, 1988) is cited (Tobin, 1992) that suggests that "even at [β] up to 60º it is unlikely that the difference in V_{50} is worth considering" for 'battlefield' fragmentation hitting aramid armour. CASPER has figures such as this in its threat database (Riach, 1997) to define the value of β above which a projectile is considered to ricochet.

Armour must cover the location of a threat's interaction with the human body in order to work. It is reported (Reches, 1978) that the total presented area, A_p, over which the threat can interact with a target is a function of the height and distance between the two. Another report (Tobin, 1992) goes further to tabulate A_p for different parts of the human body. The resistance to threats is a function of the proportion of A_p that is covered by armour.

3.3.2 Resistance to blast threats

The resistance of armour materials to blast threats is concluded from computer-based models, mechanical simulations and animal tests (Cater et al., 1990, Bell, 1991, Cooper et al., 1992, Cooper et al., 1993) to be a function of stress wave decoupling. They demonstrate that a high acoustic impedance layer, such as a fibre composite, can protect against blast wave transmission into the wearer when it is placed in front of a low acoustic layer e.g. foam. The double layer acts in the same way as double-glazing does when reducing noise transmission. Acoustic impedance mismatches at each material interface partially reflect the incident wave.

Armour resistance to blast threats is also dependent upon the covered proportion of A_p and β. In particular, it is reported (Cooper et al., 1992) that efficient coverage of all the vulnerable organs is vital if the armour is to work. This is because the blast wave interacts with an area of the person's surface as opposed to a ballistic threat, which hits more of a point.

3.3.3 Resistance to thermal threats

The resistance of armour materials to thermal threats is based on standard, one-dimensional heat transmission (Rogers & Mayhew, 1992). British standards for fire-fighters' clothing attacked by flame use this fact to define experimental test and evaluation methods of heat transmission. These dictate presenting the results as the time for a given temperature rise behind the sample of 12ºC and 24ºC (for first degree burns) (BSI, 1992); or as a ratio of transmitted to incident heat flux density (BSI, 1993).

Calver (1995) reports during consideration for the UK's Mk 5 EOD Suit that flash from the initial fireball of an explosive charge is "easily within the protective capabilities of a thin layer of flame-resistant fabric."

Armour resistance to thermal threats is also dependent upon the covered proportion of A_p and β for the same reasons as for blast protection.

3.4 ASSESSMENT OF HUMAN INCAPACITATION BY EOD THREATS

3.4.1 Estimation of the likelihood of incapacitation by ballistic threats

NATO uses the term 'survivability' to describe the likelihood of *not* being incapacitated (Ball & Calvano, 1994). This is defined as one minus the probability of incapacitation, P_i. In order to make predictions on how many people are left standing after a conflict, one needs to estimate P_i.

Semi-empirical models are available to estimate the probability of incapacitation or medical severity of wounds by a penetrating fragment (bullets are sometimes considered, incorrectly, to be pre-formed fragments). The Kokinakis-Sperrazza model (Equation 3.3) for penetration by fragments and flechettes (small, dart-like projectiles) (Kokinakis & Sperrazza, 1965) is based on work proposed first by Allen & Sperrazza (1956). It uses the mass, m, and strike velocity, V_s, of a fragment; combined with classified constants a, b and n, which depend upon the person's tactical role and body part; to predict the probability of incapacitation given a hit, $P_{i|hit}$. The constants are deduced by fitting the model to experimental data and expert judgement. Incapacitation criteria are defined by whether an injured man would be able to perform tactical roles such as a "30s assault" or "5min defence." The human body is grouped into "head & neck", "thorax", "abdomen", "pelvis", "arms & hands" and "legs & feet." Diagrammatic representation of these regions within CASPER is presented in Figures 9.5a, b &c.

$$P_{i|hit} = 1 - e^{-a\left(mV_s^{3/2} - b\right)^n} \qquad (3.3)$$

Summarised incapacitation criteria are available (Waldon et al., 1969) that use Equation 3.3 to predict "lethal" and "serious" (requiring hospitalisation) injury levels. An important point to note is that fragment penetrations to the arms & hands and legs & feet are not considered to be lethal injuries.

Davis & Neades (2002) summarise the shortcomings of the "serious-lethal" wound model (Waldon et al., 1969) as including "1) the lack of complete and detailed documentation of its development (including all rational and assumptions considered or applied), 2) is applicable only to evaluation of chunky preformed steel cube projectiles, 3) its mathematical relationship is limited to projectile mass and striking velocity parameters, 4) its mathematical relationship is generalised for anatomical body regions, 5) the use of gross anatomical injury criteria description that lacks required specificity, 6) its inability to specifically identify gradations of less serious injuries and to accurately and reliably discriminate between or rank seriousness of less-than-life threatening injuries, 7) it does not… evaluate [the] synergistic effects of multiple unique injuries that are not serious but which in combination may result in life-threatening conditions or fatality and 8) the modelling approach uses non-standard terminology compared to contemporary trauma terminology."

Two concepts that are based on P_i for calculation of incapacitation are the vulnerable area, A_v, (Equation 3.4) and mean area of effectiveness, *MAE* (Equation 3.5) (Reches, 1978). The former is the integral of $P_{i|hit}$ with respect to the presented area. The latter is the integral of the kill probability, P_k ($\equiv P_{i\ lethal}$) with respect to a given area.

$$A_v = \int_{A_P} P_{i|hit} \cdot dA \qquad (3.4)$$

$$MAE = \int_{A} P_k \cdot dA \qquad (3.5)$$

Other semi-empirical models are cited (Sellier & Kneubuehl, 1994) which use the kinetic energy (depends on V_s^2) transferred to the human body by a projectile as a basis for estimating $P_{i|hit}$. This is in contrast with the Kokinakis-Sperrazza model, which depends on $V_s^{3/2}$.

3.4.2 Estimation of the level of incapacitation – trauma scores

The reverse of quantifying the likelihood of incapacitation for a given criteria is establishing the level of injury for a guaranteed hit. The latter approach is carried out using trauma scores based on the ideas behind medical triage. Davis & Neades (2002) summarise and cite references for the Abbreviated Injury Scale (AIS), Injury Severity Score (ISS), Anatomic Profile, Modified-Anatomic Profile, Anatomic Profile Score and New Injury Severity Score. They are derived from medical opinion of the severity of different injury types. Davis & Neades advocate the use of trauma scores for the evaluation of body armour against ballistic threats.

3.4.3 Estimation of likelihood of incapacitation by blast threats

Mechanisms for blast incapacitation are divided into three categories: primary, secondary and tertiary. Smith & Hetherington (1994) state that "Primary injury is due directly to blast wave overpressure and duration which can be combined to form specific impulse… The location of most severe injuries is where density differences between adjacent body tissues are greatest. Likely damage sites thus include the lungs which are prone to haemorrhage and oedema… the ears… and the abdominal cavity." Secondary blast injuries are those due to missiles such as fragmentation from the blast. Tertiary injury is due to the displacement of the entire body or limbs.

The classic primary blast injury is 'blast lung.' The likelihood of this is estimated by Bowen et al's (1968) curves for a 70kg man in a given orientation to the blast wave and reflecting surfaces. These are plotted on axes of overpressure positive phase duration. Figure 3.6 shows the curves for a man, remote from reflecting surfaces, with his long axis perpendicular to the direction of travel of the blast wave.

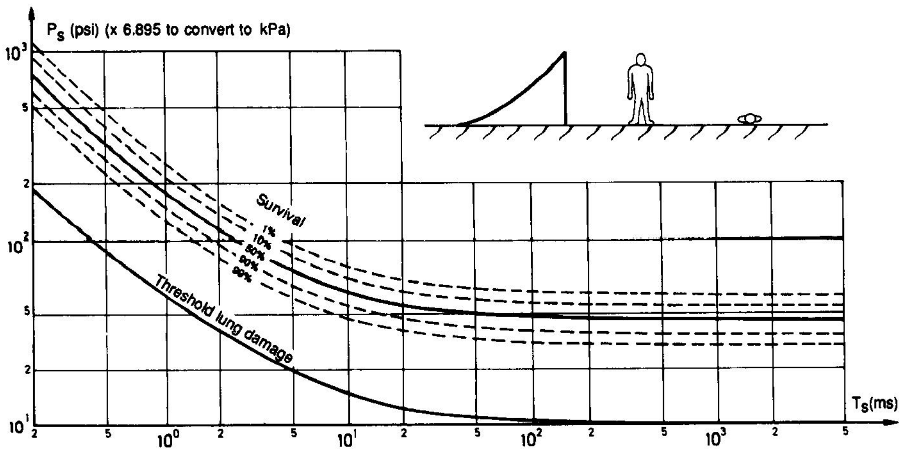


Figure 3.6: Survival curves for a 70kg man, remote from reflecting surfaces, with his long axis perpendicular to the direction of travel of the blast wave (Bowen et al., 1968)

The eardrum is a great deal more sensitive to blast than the lungs. Figure 3.7 shows curves derived (Richmond & White, 1966) to estimate eardrum rupture as a function of overpressure and duration.

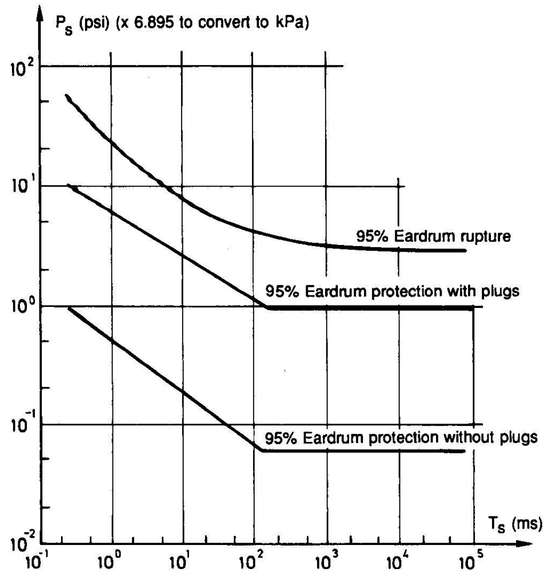


Figure 3.7: Eardrum rupture curves for man (Richmond & White, 1966)

3.5 CASUALTY REDUCTION ANALYSIS SOFTWARE

3.5.1 CASPER

The steps of threat evaluation, estimation of armour resistance and human vulnerability assessment are combined in the topic of casualty reduction analysis (Tobin, 1992). Computer software is used in many NATO countries to deal with the volume of information processed for this task. The UK has a program named CASPER (Hunting Engineering, 1999) that is used to assess the likelihood of casualties through exposure to fragmentation munitions and bullets. CASPER estimates the position and velocities of each fragment from an exploding device. *It does not assess the blast or thermal threat.* The action of any shielding or armour is included before the effect on the person is determined. For example, it is used to simulate the effect of an 81mm mortar on a person with and without a GS Mk 6 helmet and CBA vest (Grout, 2000). It allows Grout to discuss the benefit of armour for this threat at a variety of ranges, elevations and heights at detonation.

Threat files have the extension '*.wpn'. They define the fragment initial velocities relative to the point of detonation, masses, area coefficients, materials, drag coefficients, ricochet angles and distribution in angular bands *along* an axis of rotational symmetry (Figure 3.8). CASPER contains a database (Riach, 1997) of pre-defined threats that are based on arena fragmentation trials (Section 3.2.1). There is also the facility to enter more threats to suit the particular operational scenario. Currently, only the fragmentation characteristics of explosive munitions are simulated by the model. No account of blast or thermal threats is included.

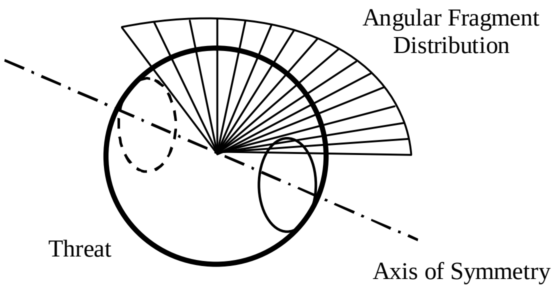


Figure 3.8: Fragment distribution in CASPER in angular bands along the axis of symmetry

A munition has a position in space, orientation and velocity. The user inputs the set of its height, range, azimuth, elevation, initial velocity, ranges and angles around the man at detonation for each run.

Each fragment's trajectory is simulated by the shotline method, from the point of threat detonation to the target. Each shotline is a potential diverging path from the threat (Figure 3.9). Air drag is applied to the fragment to calculate the velocity as it hits the active plane of any shielding and then the target. Shielding in CASPER is not used in this report and is described elsewhere (Hunting Engineering, 1997, Grout, 2000).

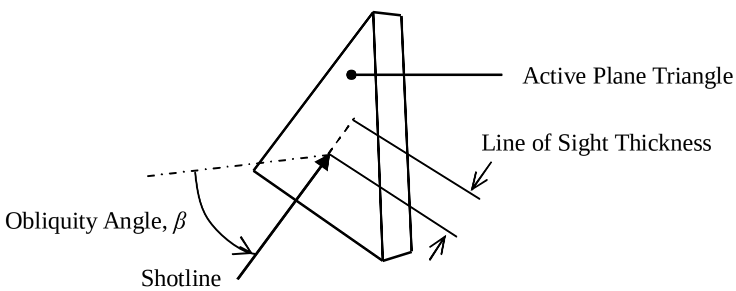


Figure 3.9: Triangulated surface geometry of the target

A target comprises of a man plus any armour. The man is modelled in a static posture at the centre of the simulation. Pre-defined postures named 'crouched', 'kneeling', 'standing', 'sitting' and 'prone' are available in CASPER (Hunting Engineering, 1997). The geometry files have the designation '*.geo'. These are based upon standardised NATO target data (NATO, 1995) of a 1.75m man (Figure 3.10). In particular, the 'crouched' character is also known as the 'advancing man' and represents a slightly stooped, moving person. There is a facility to modify or develop new postures.

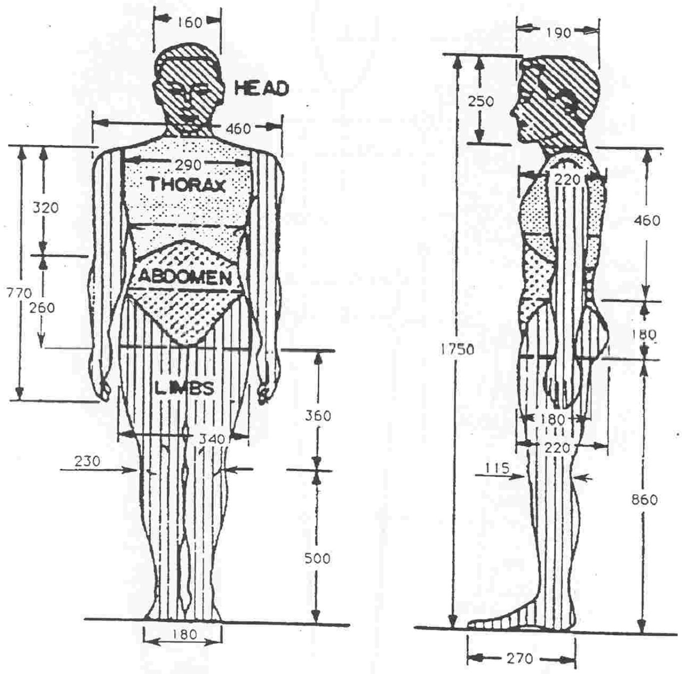


Figure 3.10: Body dimensions in mm (NATO, 1995)

Armour is represented in a *.geo file of triangulated three-dimensional geometry. Models that approximate the GS Mk6 Helmet, CBA and Lightweight Combat EOD Suit (Section 2.2) are available in CASPER. There is a facility to adapt existing armours or introduce new ones. A garment is divided into parts, each with its own material code. Materials information contained within a *.mdb file is assigned to the geometry based upon the code.

The materials database includes options to model a material as (1) impenetrable or (2) as having a V_s-V_r profile (Equation 3.2). The latter option means that any fragment with a strike velocity, V_s, above the limit velocity, V_L, will perforate the armour with a residual velocity, V_r. Each layer of armour is assessed in succession, starting with the outermost. Interpolation is used to calculate the value of V_L for each fragment using Equation 3.6. V_{L1} and V_{L2} are the V_L values for the lower (m_1) and higher (m_2) database fragment masses, and m is the fragment mass produced by the threat.

$$V_L = V_{L1} + \frac{(m - m_1)(V_{L2} - V_{L1})}{(m_2 - m_1)} \tag{3.6}$$

If a fragment perforates all the armour, the person is classed as a *casualty*. The probability of this is P_c. The fragment's residual velocity becomes the strike velocity in the Kokinakis-Sperrazza equation as first proposed by Allen and Sperrazza (1956) (Equation 3.3). There is a facility to use the summarised Kokinakis-Sperrazza incapacitation criteria (Waldon et al., 1969) of *serious* and *lethal*, in addition to the full criteria (Kokinakis & Sperrazza, 1965). The values of P_c and P_i are calculated for both *armoured* and *unarmoured* targets.

CASPER calculates a value of P_i for each fragment and each incapacitation criterion. The P_c and P_i values for individual impacts are combined binomially within the same Kokinakis-Sperrazza body region (Section 3.4.1, Figures 9.5a, b & c). These regional values are presented separately and also combined binomially to give the overall probability of incapacitation for the chosen criterion.

The output from CASPER includes the P_c and P_i for the armoured and unarmoured man. P_c unarmoured equals the probability of being hit. P_i with and without armour is used to obtain the percentage reduction in casualties, *%CasRed* (Equation 3.7).

$$\%CasRed = \left(1 - \frac{P_{i\ armour}}{P_{i\ unprotected}}\right) \times 100 \tag{3.7}$$

3.5.2 ComputerMan

CASPER is not the only casualty reduction analysis program to exist. Reviews of software in the early 1990s (Tobin, 1992, Hunting Engineering, 1993) highlight ComputerMan (Saucier & Kash, 1994) in the USA, MIC in France and Timberwolf in The Netherlands. Use of the former continues to be presented in open literature. For example, ComputerMan is used (Jager et al., 2004) as a design tool for the Netherlands Soldier Modernisation Programme. The most significant difference between ComputerMan and CASPER is that it has the option to use the Injury Severity Score (ISS) (Section 3.4.2) as an assessment tool. A model of a person can be presented with a colour map of the different score levels for different parts of the body.

3.6 EVALUATION OF PERSONAL ARMOUR ERGONOMICS

3.6.1 A selection of personal armour ergonomics issues

Ergonomics, otherwise known as 'human factors,' is a human-centred systems science. It is the interaction of people and their surroundings that make the person more or less able to carry out their job. For example, a UK Woman Police Constable was stabbed to death in 1998 after removing her armour because her movements were restricted to the extent that she could not operate a battering ram with it on (Steele, 1998).

Calver (1995) discusses issues involving the Mk 5 EOD Suit. He considers the system requirements for weight, mobility & dexterity, temperature management, field of view & visual clarity (e.g. as a function of misting), hearing, communication, size and the ability to don or doff the suit. Kelm (1996) considers the impact of restricted communication, manual dexterity, restricted vision, overheating and psychological aspects for wearer's of NBC suits – close cousins of EOD suits.

Ashby et al (2004) study 6 fit, male soldiers' reductions in speed and shooting accuracy, and increases in the time to complete, *TTC*, an assault course for 6 different armour weight plus equipment (weapon, webbing and helmet), equipment only and no kit. The armours vary from 2.2 to 12.6kg and the equipment is 16kg. Subjects complete a 500m assault course, 400m fire and manoeuvre exercise, 200m fireman's carry on flat ground, 10m rope climb and target shoot. They are assessed on the *TTC* the first three tasks and shooting accuracy, and any inability to complete an activity is recorded. Figure 3.11 is a graph of Ashby et al's tabulated data.

Cases of localised weight distribution are reported (Bhatt, 1990) for soldiers providing top cover (raised weapon) out of a vehicle: the weight of armour pressing on the brachial plexus leads to a loss of function in the left arm. Dean & Newland (2002) report that "85% of [US soldiers in Afghanistan] complained that [the PASGT] helmet is too heavy, causing long term headaches and neck pain…" and "the arm holes [of Interceptor Body Armor] are too small and that [soldiers] lose circulation in their arms, especially when wearing their rucksacks."

A set of tasks devised by the US for assessing the degradation of mobility, dexterity and field of view due to wearing EOD suits is described by Calver (1995) and presented in Table 3.2.

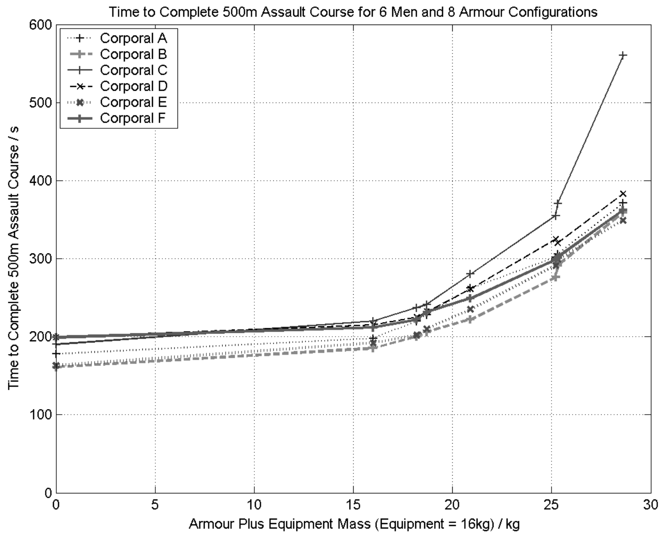


Figure 3.11: Time to complete, *TTC*, a 500m assault course for 8 armour configurations – graph of tabulated data by Ashby et al (2004)

Evaluation Group	Tasks / Tests
Gross Body Mobility	Walk forward five steps
	Walk backward five steps
	Side step five steps
	Standing trunk flexion (three toe touches)
	Head rotation (bent forward at waist)
	Ventral-dorsal head flexion
	Upper arm abduction
	Upper arm forward extension
	Upper arm backward extension
	Upper leg abduction
	Upper leg forward extension
	Upper leg backward extension
	Upper leg flexion
	Sitting trunk flexion
	Kneel and rise
Psychomotor Tasks	O'Connor fine finger dexterity task
	Cord and cylinder manipulation task
	Pursuit rotor task
Speech Intelligibility	Modified rhyme test (consonant differentiation in monosyllabic word sets)
Visual Field Investigation	Determination of periphery of visual field by detection of movable illuminated target (head held static)

Table 3.2: US EOD suit evaluation tasks and tests (described by Calver, 1995)

Havenith (1999) demonstrates the importance of clothing properties to a person's thermal stress. He summarises that heat and vapour resistance are a function of the type and number of clothing layers, the enclosed air layers, the clothing fit and its design i.e. ventilation openings. Havenith suggests that clothing heat and vapour resistance can be estimated by use of thermal manikins, heat balance using human subjects, prediction models, regression equations and example tables.

Withey (2001) discusses the physiological limits of the human body. For example, the need for the human body to maintain a constant deep-body temperature, T_{db}, of approximately 37ºC is discussed. Withey states that "A rise of 1.0ºC is the maximum permissible rise in an industrial workforce and causes a measurable decline in physical and mental performance. A rise of 2.0ºC is dangerous and borders on a medical emergency because the thermoregulatory mechanisms begin to fail."

Wearing protective clothing increases the rate of heat storage (S) within a person by increasing the metabolic heat generation (M - W) and reducing the heat loss through evaporation (E), radiation (R), convection (C) and conduction (K) (Parsons, 1993) (Equation 3.8). M is the metabolic rate of the body and W is the work exerted on the world.

$$S = (M - W) - E - R - C - K \tag{3.8}$$

Haisman & Goldman (1974) evaluate the thermal response (rectal temperature, T_{re}) of 8 men walking with 25.6kg loads in hot-wet (35ºC, 70% relative humidity) and hot-dry (48.9ºC, 70% relative humidity) in order to compare the effect of wearing a standard (std), lightweight (lt) or no armour vest worn over a tropical uniform. The task is to walk on a level treadmill at $1.12 ms^{-1}$ for two periods of 50mins with a 15 min rest interval, on the day following an acclimatisation session. The subjects are allowed cool (14ºC) water to drink *ad libitum*. Garments are worn closed for the entire session. Measurements are taken of the sweat evaporated, heart rate, T_{re}, skin temperature and heat storage. The increase in rate of rectal temperature gain as a function of time for the 3 armour combinations within the hot-dry environment is presented in Figure 3.12.

Calver (1995) discusses the use of inner cooling suits to increase K. These pump coolant such as ice water around the body and are used in planes where the pilot does not have to carry round the extra burden of the refrigeration unit. K and E can be increased by reducing the thermal and moisture resistance of armour (Havenith et al., 1990b, Parsons, 1993). Armour is now available that absorbs heat for a limited duration (Protective Apparel Corporation of America, 2000) by melting wax phase change micro beads (Outlast Tech., 2004) An alternative approach is to increase C by using constructions that allow the flow of air around the body (Havenith et al., 1990a). For example, 3-dimensional weave fabrics are now available that encourage air flow (Müller Textil, 2004).

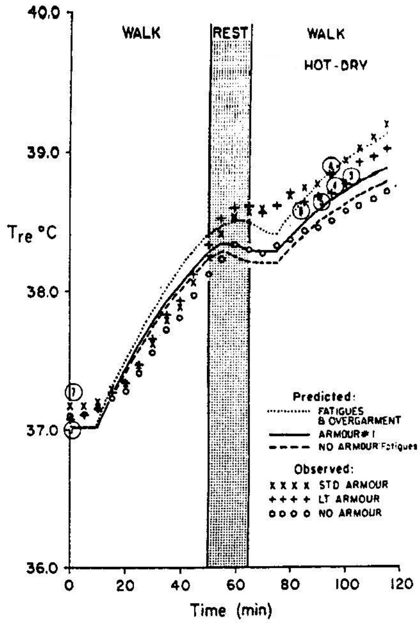


Figure 3.12: Rectal temperature, T_{re}, for 3 armour configurations in a hot-dry environment (Haisman & Goldman, 1974)

3.6.2 Materials assessment

Materials assessment is used to select the most promising combinations of fabrics. Calver (1995) describes the primary ergonomic constraint of EOD suits – weight – as being the combination of surface area and areal density (mass per unit area) to achieve a given protection level within gravitational acceleration.

Congalton (1995) evaluates the heat and moisture transfer properties of ballistic nylon and para-aramid packs (of 4 to 31 flat layers) under steady state conditions. The test apparatus is a ‘sweating skin’ model for which ISO 11092 (1993) is cited. This is a computer-controlled, sweating, guarded hot-plate that supplies a steady, measurable flow of heat and water-vapour, within a climatic chamber. The results are given as thermal and water-vapour resistances, and water-vapour permeability for each assembled pack of material.

Missihoun et al (1998) compare methods of testing the flexibility of flat armour samples. Two methods are the rectangular cantilever and modified circular bend tests. The former measures the length of sample overhanging a platform when it depresses under its own weight to a specified angle. The latter uses a hemispherical indenter to push fabric into a circular orifice in a platform. Missihoun concludes that the modified circular bend test appears to be the most accurate and takes into account the bi-directional stiffness of armour materials.

3.6.3 Garment testing without a wearer

Egglestone & Robinson (1999) use a sweating hotplate similar to the one used by Congalton (1995) to determine the heat and water-vapour transfer properties of helmet material. They then use a 3-dimensional helmet on a manikin in a wind tunnel to measure the airflow around the head at air speeds of 0.5 to $2.0ms^{-1}$. The two sets of results are combined to assess the venting in different helmet configurations to reduce heat strain on the wearer. Egglestone & Robinson conclude that "the most efficient air gap was found to be one that provided flow-through ventilation from the front to the rear."

Performance tests and manikins for the assessment of heat stress as affected by clothing are described by Holmér (1999). The differences between 'performance' and 'evaluation' standards are: the former are based on the transfer properties of materials in defined environments; the latter are used to evaluate the strain on the human body for any environment or task. Holmér discusses the benefits of evaluation using manikins compared with performance tests. For example, a "walking" thermal manikin records typically 10 to 30% lower heat insulation than for static assessment as a result of movement pumping air around a garment. Parsons (1993) describes a sweating manikin that is the step beyond the materials test described by Congalton (1995).

3.6.3 Garment testing with a wearer

Tests for mobility are conducted for NASA spacesuits (Gonzalez et al., 2002) by isolating the movement of single joints and getting 3 female and 3 male test subjects to repeat actions until they cannot continue. The torque generated by each joint, angular movement, duration and number of repetitions is measured. This also allows the calculation of the decrease in work exerted by each joint as a result of wearing a protective suit.

Smee et al (1982) conduct a human factors assessment of a Searcher's Suit, which is designed to protect against fragmentation from explosive ordnance rather than blast. Trials are carried out with 8 male soldiers to study the effect of wearing the suit on: functional reach for a set of movements, lung function (peak flow rate), time to complete, *TTC*, an agility course at a sprint, *TTC* a 2.4 km run, *TTC* crouching and crawling and *TTC* a 4.8 km walk. The results are presented as the percentage reductions in movement by linear distance, decrease in peak flow rate and *TTC* the timed activities.

Widdows (1991) assess the effect of wearing Combat Body Armour (CBA) on the performance of heavy goods vehicle (HGV) drivers. The test subjects are 12 male soldiers, all of whom are qualified HGV drivers but are inexperienced at driving an 8-tonne truck. They are assigned randomly to a group that either wears CBA plus GS Mk 6 Helmet or does not. The men are then asked to perform a series of approximately 5 practice runs and 5 experimental runs, to the best of their ability, around reversing and slalom courses marked out by cones. Two types of objective measures are taken for each run: the *TTC* the course and the number of errors (e.g. touching marker cones). Statistical analysis is used to test the significance of the difference in these measures with and without armour. The results suggest that there is no degradation in the performance of HGV drivers due to wearing CBA. Subjective responses from the subjects state that some found CBA made them too warm and is cumbersome, but is acceptable overall.

Kistemaker et al (2004) quantify the degradation in performance due to wearing body armour during user trials. 8 male subjects perform shooting, driving, crawling and circuit tasks after a practice run. The men carry out physical exercise (dexterity test, arm cranking and walking on a treadmill with a 20kg backpack). The tasks are assessed by the deviation from the shooting target and the driving course; the *TTC* and visible surface area during the crawl; the *TTC* the circuit and maximum jump height. Additionally, the increase in heart rate, skin temperature, rectal temperature, number of pegs put in a dexterity test board in a given time and mood profile are recorded. The significant conclusions are that wearing the body armour increases the visible surface are of test subjects during the crawl, *TTC* the circuit, heart rate, thermal burden and psychological load (tension, depression, vigour, fatigue), and decreases the jumping height.

Amos et al (1998) studies a methodology for assessing the physiological strain on enhanced soldiers. The subjects are 10 male soldiers in hot-wet and hot-dry field environments. One of the variables is Australian combat body armour. 4 groups of tasks are considered: patrol, observation post, assault, entire operation. The following parameters are measured: oxygen consumption, deep body and skin temperatures, heart rate, hydration (from the change in men's weight minus intake of food and fluids), environmental temperatures and wind speeds. Amos et al note practical difficulties in obtaining such data in the field, especially T_{re}; and variations in experimental conditions between time of day, duration of patrol, route differences and environmental conditions.

Edwards & Tobin (1990) carry out a user trial with 2000 items of combat body armour (CBA) over four to eight months duration, predominantly in northern Europe. Feedback is collected via a questionnaire on the following requirements: weight and body coverage; body flexibility; suitability for driving; compatibility with weapon operations, other clothing, helmet, respirator, webbing and vehicles; thermal burden. Consequently, suggestions are made for the modification and use of CBA.

3.7 TRADE-OFF BETWEEN PROTECTION AND ERGONOMICS

Dean & Newland (2002) present qualitative feedback of the likes and dislikes that armour wearers feel towards their equipment. This allows wearers to make a subjective trade off between the ergonomic degradation due to personal armour and their *perception* of the protection offered.

A basic objective trade off between ballistic protection and ergonomics is to compare the V_{50} of a material for a specified projectile and its areal density, as carried out by Tobin (1985). If the surface area of a garment is defined, the next step is to relate its weight to the protection offered. Gotts (1999a) uses CASPER to estimate P_i for a person wearing garments of different weights.

Ashby et al (2004) use velocity data gathered in their ergonomics trials (Section 3.6.1) and estimates on the percentage of fragments and HV bullets stopped by 6 armours. This is entered into an operational analysis (OA) computer-based war-gamming simulation named Janus (US Army, 1997). The 'blue' force is modelled as attacking a 'dug in' 'red' force (the enemy). There is a ratio of 10 blue soldiers to 3 red ones. The defenders have 10 82mm mortars, 5.56mm rifles and 1 sniper with a 0.5" sniper rifle. The blue force has 5.56mm assault rifles. Table 3.3 is Ashby et al's results of the total number of casualties predicted to be sustained during the successful (all red combatants eliminated) assault for 6 weights of armour.

Armour weight / kg	Predicted blue casualties / %
0	71
2.2	69
2.7	69
4.9	69
9.3	77
9.2	77
12.6	83

Table 3.3: Predicted Percentage of casualties to successfully assault a dug in force for 6 armours (after Ashby et al., 2004)

Wilson et al (2000) define trade-offs metrics for OA for the UK's Future Integrated Soldier Technology (FIST) programme. They state that metrics should be sufficient to span the range of capabilities of both current and future human systems; must be quantifiable; should be broadly independent as there is little advantage in specifying a large number of highly related capabilities.

Lotens (2004) provides a schematic framework in open literature that combines protection, mobility, lethality, sustainability and command & control capabilities together with mission plans and enemy predictions.

3.8 TRADE-OFF BETWEEN PROTECTION AND FINANCIAL COST

The relative costs of armour materials to defeat a 7.62mm NATO armour-piercing round are presented by Roberson (1995) (Figure 3.13)

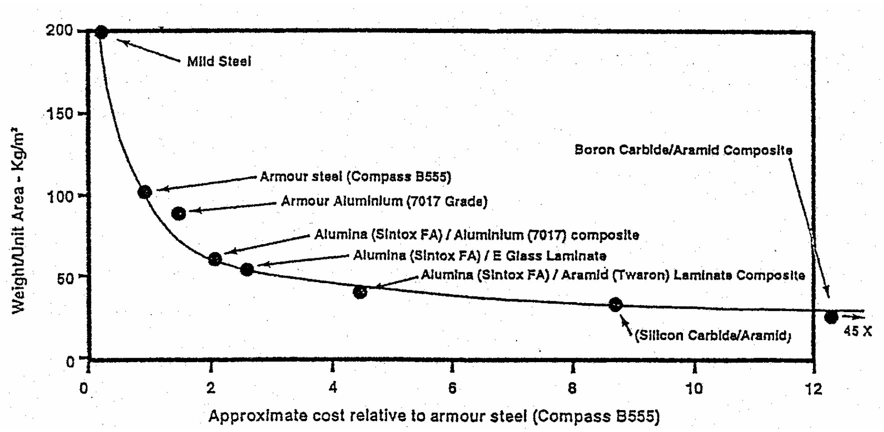


Figure 3.13: Relative costs of armour materials to defeat a 7.62mm NATO armour-piercing round

3.9 CONCLUSIONS

1. Ballistic threats are divided into bullets and fragments. They are classified according to factors such as their mass, strike velocity, shape and material. Fragments are further categorised as primary ('battlefield' and high energy) and secondary fragmentation. 'Battlefield' fragmentation is smaller and slower for the same range than the high energy variety. Secondary fragmentation is not part of the initial explosive device and includes stones thrown up from an approximately conical crater during an AP blast mine detonation.

2. Blast threats are characterised by the peak overpressure, duration, impulse, range, reflecting surfaces and charge energy compared to a specified mass of TNT. The destructive potential of conventional explosive ordnance decays rapidly with range. Thermobaric weapons are now available on the world market, which inflict significant blast energy to a greater range than is possible for an equivalent conventional device.

3. Thermal threats are divided into flash and flame. Flash is generated by the initial fireball of an explosion. Flame is produced by immersion in burning materials such as napalm. Flash is of much shorter duration than flame.

4. Fragmentation threats dominated mid-20th century warfare. An increasing proportion of threats faced by soldiers are from HV bullets. Nevertheless, the threat to EOD personnel is predominately, though not wholly, from fragmentation, blast and heat. The dominance of these three depends upon factors including the range and type of device involved.

5. Ballistic threats are resisted by soft and hard armour over an area of coverage, and by the incidence geometry. The ability of materials to resist bullets and fragments is assessed using go-no go proof tests, estimation of the velocity at which a given proportion of projectile will perforate and calculation of the residual properties after impact. The kinetic energy of a given projectile is a commonly used predictor of ballistic performance. However, this is an approximation and momentum may be a better predictor for alternative projectile-target combinations.

6. Blast threats are resisted by stress wave decoupling and incidence geometry. Their defeat depends on covering the whole vulnerable area of the body.

7. Thermal threats are resisted for a given duration by the heat resistance of armour as predicted by standard one-dimensional heat transfer. Calver (1995) states that flash from conventional munitions is "easily within the protective capabilities of a thin layer of flame-resistant fabric."

8. Incapacitation is estimated either as a probability, for a given criterion, or a level for a given hit. The former is used in the Kokinakis-Sperrazza model (Allen & Sperrazza, 1956) using Waldon et al's (1969) lethal and serious summarised incapacitation criteria. It is also used in Bowen et al's (1968) curves for blast injury. The latter is used as the basis of trauma scores.

9. Casualty reduction analysis combines the stages of threat evaluation, armour resistance and human vulnerability. CASPER is a UK computer simulation that uses the Kokinakis-Sperrazza model to assess protection offered against fragmenting munitions but does not include the blast or thermal threats of such devices. ComputerMan is a US alternative that has the facility to present results for the ISS trauma scoring system.

10. Ergonomic burdens of armour include its weight, flexibility, heat and moisture resistance, field of view, acoustic impedance and visual clarity. These cause the wearer to have factors such as greater fatigue, overheating, reduced movement, restricted vision, restricted hearing, and reduced speed.

11. Ergonomic evaluation is carried out by materials assessment, garment trials with the wearer and garment trials without the wearer. Materials are assessed for measures such as areal density, heat and moisture resistance, and flexibility. Garment trials without the wearer allow evaluation of the item as a whole. Examples include calculation of the total weight and heat flow through and around the armour. Garment trials with a wearer provide measures of system emergent properties such as the time to complete tasks, error rate, temperature gain, hydration loss and range of movement.

12. System trade-offs require metrics that are sufficient, quantifiable and independent. Existing examples in increasing complexity are: comparing the ballistic limit of a material against its areal density or relative financial cost; balancing the weight of a garment against the probability that the wearer is incapacitated; estimation of the number of casualties taken to complete a task successfully.

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CHAPTER 4: RESEARCH AIMS

4.1 INTRODUCTION

4.1.1 Aims

To derive the research aims of this thesis from the rationale given in Chapter 1, subject fundamentals described in Chapter 2 and current state of the art presented in Chapter 3.

4.1.2 Objectives

- Identify novel activities that extend knowledge of the personal armour design system,
- Coordinate research aims with work that supports development of the Lightweight Combat EOD Suit and Mk 5 EOD Suit where appropriate,
- Structure the activities in a logical progression,
- Discuss the limitations of the research aims.

4.1.3 Background

The wide variety of sometimes disparate subjects included in the background information and literature review chapters illustrates the complexity of real personal armour systems. Moreover, each topic has a different level of sophistication given the current state of knowledge. Part of the novelty of this thesis is to refine those subjects: to give them greater depth. Part is to link them together more rigorously: to enhance the system breadth. There is a seemingly infinite array of questions to answer but some are more important – through influence or urgency – than others. Hence, a selection of topics with novel aims is chosen that either have strong influence on the system or urgency for the needs of the sponsors, DLO DC R&PS.

A proper systems approach combines both ‘top-down’ (goal focussed) and ‘bottom-up’ (potential driven) views of a problem. The systems engineer must aim for the desired output within the constraints of possibility. It is traditional to decompose the system to gain knowledge before reconstruction as represented by the “Vee model” (Forsberg & Mooz, 1992) (Figure 2.29) cited by Buede (2000). Thus, the progression of the aims is of breadth to depth to breadth again as illustrated in Figure 1.1. Research activities are targeted to (i) provide a framework to describe the system, (ii) refine the primary benefit of armour, (iii) assess a single input to calculation of that benefit for the Lightweight Combat EOD Suit, (iv) review the major constraint of armour and (v) synthesize the system in order to optimise personal armour design.

4.2 ELICITATION OF PERSONAL ARMOUR DESIGN

Chapter 3 illustrates that the state of the art in and around personal armour design contains a large number of fragments of knowledge. Some are larger than others; some are more detailed. These pieces are unified in the real world but are dissected in order to be comprehended by the human mind. They must be grouped into coherent chunks that can be unified into models. These can then be compared to real world cases. This is not the creation of novel system architecture: it is the description of its structure.

Chapter 2 introduces the concept of 'boundary' in order to limit information gathering to that which is useful and feasible. Chapter 1 provides the basis for defining the boundary in the statement that "'A systems approach to personal armour design' [means] considering… individual, man-portable, defensive coverings within the context in which they are to be used." Consequently, literature in Chapter 3 on e.g. threat evaluation and human vulnerability may be considered to be components within the system boundary. Alternatively, information on soldier systems (Lotens, 2004) includes topics such as lethality of an armour wearer, which is primarily the concern of weapon rather than armour designers. This falls outside of the system of interest. A boundary must be defined carefully in order to sort knowledge into those portions that concern personal armour design directly and those that do not.

The personal armour designer does not have complete control over everything within the system boundary. He or she can specify what armour is constructed but has little influence over who uses it or what weapons an enemy chooses to use. Definition of the designer's levels of control is required in order to identify gradations of the system boundary.

The concept of 'system hierarchy' is introduced in Chapter 2. This allows the designer to consider personal armour to be comprised of distinct but interlinked subsystems. The concept of 'emergent properties' allows subsystems to be based on the benefits and penalties of armour. These form the 'coherent chunks' described above that are broken out in Chapters 6 and 8. Moreover, the designer can consider the personal armour system to fall within a larger system such as the trade off between protection, firepower and mobility to achieve mission success (Ashby et al., 2004).

It is proposed by the author that the process of modelling the real world is carried out continuously by every armour designer; otherwise they could not justify design decisions. However, that does not mean that all mental models are explicit and can be shared. Integration of the knowledge of many different researchers given in Chapter 3 requires a framework that is written down. Currently, the closest approximations to are either the architectures of casualty reduction simulations such as CASPER (Hunting Engineering, 1999) or integrated soldier system design methodologies, for instance that used in The Netherlands (Lotens, 2004). The former only covers a portion of the system, i.e. not including ergonomic or financial cost penalties. The latter operates at a higher level than that required by the personal armour designer.

The objectives of Chapter 5 are therefore to provide an explicit, holistic framework in which to understand personal armour design by (i) identifying an appropriate boundary, (ii) defining the level of control that the designer has over the various inputs, (iii) eliciting the system hierarchy used to deconstruct the system in Chapters 6 to 8 and (iv) deducing the emergent properties that are traded-off in the synthesis of Chapter 9.

4.3 MEASUREMENT & MODELLING OF PROTECTION

Trade-offs at the system-level require definition and measurement of the primary benefit of armour – protection. Current NATO military terminology uses the word survivability to describe the likelihood of not being incapacitated (Ball & Calvano, 1994). This is defined as one minus the probability of being incapacitated, P_i. This does not differentiate between the benefits of armour, defensive or offensive tactics in reducing P_i. Survivability can be increased by removing an assailant's capability or intent to harm, or by staying out of range, as well as through the use of armour. Moreover, there is no relationship between the armoured and unarmoured states. Hence, protection is only a part of survivability and needs separate definition and measurement.

In the UK military, a commonly stated hierarchy of objectives to maximise vehicle survivability is : "(1) Don't be encountered; (2) If encountered, don't be seen; (3) If seen, don't be acquired; (4) If acquired, don't be hit; (5) If hit, don't be penetrated; (6) If penetrated, don't be destroyed." This chain is helpful because it highlights that a series of events must happen in order for a threat to incapacitate a person. However, this too is subject to the constraints listed in the previous paragraph. Furthermore, there is no evidence of feedback to demonstrate the trade-off between e.g. step 3 (be fast) and step 5 (use armour, which reduces mobility).

Current measures of protection include the go-no go trials in proof tests (NIJ, 2000, 2001, Croft, 2003b, a). These do have a basic measure of protection since they assess the likelihood of incapacitation with and without armour as a binary state. However, this is simplistic since e.g. areas outside the area of coverage are not included.

Casualty reduction analysis simulations such as CASPER (Hunting Engineering, 1999) use P_i for various incapacitation criteria (Waldon et al., 1969) (equivalent to P_k for lethal incapacitation). These are measures of incapacitation rather than protection since no comparison is made – within the measure – between the armoured and unarmoured states. Measures such as the vulnerable area A_V and mean area of effectiveness (*MAE*) (Reches, 1978) are in essence proxies of P_i and subject to the same limitation.

CASPER also uses the percentage reduction in casualties, *%CasRed*, which does compare the benefit between the armoured and unarmoured states but is limited because it excludes the effect of e.g. staying at the edge of the threat range as described in Table 6.1.

In addition to P_i, ComputerMan (Saucier & Kash, 1994) uses the Injury Severity Score (ISS), which is described in the proceedings of PASS2002 (Davis & Neades, 2002). These scoring systems are derived fundamentally from the ideas behind medical triage. Hence, they introduce bias between the severity of different incapacitation levels if used to compare between the effects with and without armour. If trauma scoring is used, then the designer – and not the wearer – is specifying relative weighting of such subjects as permanent disablement and death. It is the author's belief that this is undesirable. A preferable solution is to provide the wearer or commander with clear information so that the decision is made by the person or people that accept the consequences.

The objectives of Chapter 6 are therefore to (i) describe the protection subsystem in appropriate detail, (ii) identify a measure of protection effectiveness that accounts for the actual benefit of armour and (iii) demonstrate the novel use of casualty reduction analysis software to assess protection by using the Lightweight Combat EOD Suit as a case study.

4.4 SECONDARY FRAGMENTATION FROM AP BLAST MINES

During the course of this research, DLO DC R&PS (formerly DCTA) produced the Lightweight Combat EOD Suit (Gotts, 2000). This includes a degree of protection against one of the world's most prolific threats (ICBL, 2001) – antipersonnel (AP) landmines (Chapter 2.3.1). The effects of primary fragmentation can be assessed using CASPER (Hunting Engineering, 1999), fragment simulating projectiles (FSPs) such as those defined in STANAG 2920 (NATO, 1996) and arena trials against suitable fragmenting munitions.

The current test methodologies for personal protective equipment (PPE) against AP mine blast are covered thoroughly in the final report of a recent NATO technical working group (NATO, 2003). This details procedures to assess the effects of the primary blast threat to the upper and lower body. However, there is no assessment of the threat of secondary fragmentation from buried AP blast mines, i.e. stones and other debris contained in the soil.

It is well known (Cooper, 1996) that material surrounding explosive buried close to the surface is thrown up in a cone from a crater. Canadian researchers (NATO, 2003) x-ray the early deformation of the soil cap above a 100 gram charge buried under 30mm of sand. This gives the shape of the matter as it accelerates. Two frames in close succession could be used to obtain rough velocities but there is no sensible way to infer the probabilities of being hit and the effects of fragment mass from these pictures.

Research of unconstrained secondary fragmentation is cited (Baker et al., 1983) and carried out in an MSc thesis (Valasis, 2003) in addition to citation of work on constrained material (Westine, 1977). However, the secondary fragments around a mine are neither unconstrained – since they are packed in soil – nor fully constrained because the soil is relatively weak in tension. Moreover, the geometric distribution of material around a mine means that the aforementioned models are not directly applicable. Hence, there is a need for further analysis of secondary fragmentation from buried AP blast mines.

The DCTA trials that accompany the Lightweight EOD Suit development (Gotts, 2000) include detonation of bare explosive charges in pits of stones against prototype garments and strawboard targets. The latter can be calibrated for individual impacts in a similar manner to that used for metallic fragments (McMahon, 1971) in order to assess secondary fragmentation. This may be understood as an input to the protection subsystem developed for the research aims of Section 4.3.

The objectives of Chapter 7 are therefore to assess the threat from secondary fragmentation from buried AP blast mines in terms of (i) the probability of being hit, (ii) the probability of a hit perforating armour and (iii) the probability of a hit incapacitating an unarmoured person, by calibration of DCTA trials data.

4.5 SUGGESTIONS FOR ERGONOMIC EFFECTIVENESS ASSESSMENT

The degradation in ergonomic effectiveness – the change in the ability of the wearer to complete his or her job – is the main, tactical penalty of personal armour. During this project, DLO DC R&PS produced the Mk 5 EOD Suit (Calver, 1995). This has the potential to prevent the wearer from working due to visor misting. Calver produced an electrically heated demister to tackle this problem, although this is not listed in his report. Analysis of its operation provides a simple opportunity to demonstrate how ergonomic design can minimise the burden on a wearer.

A review of the state of the art in Chapter 3 finds that authors measure a range of factors to evaluate personal armour. Materials assessment such as the use of areal density or flexibility tests (Missihoun et al., 1998) is employed to select the most promising combinations and constructions of fabrics. Garment testing *without* the wearer provides information on e.g. air flow through an item (Egglestone & Robinson, 1999). Garment testing *with* the wearer is the highest level and most representative types of assessment for personal armour design. It uses real wearers and armour, and realistic tasks such as assault courses (Ashby et al., 2004, Kistemaker et al., 2004) and extended trials exercises (Edwards & Tobin, 1990b). They use measures such as the time to complete a task and the proportion of people who complete an exercise successfully, in addition to qualitative descriptions of problems. These three types of ergonomics assessment assess three different system levels. However, when it comes to specifying a personal armour system, there seems to be a tendency to define requirements at different system-levels and treat them equally. For example, Calver (1995) lists 'weight' and 'mobility' as equal requirements of the Mk 5 EOD Suit, while Edwards & Tobin (1990a) evaluate 'weight' and 'body flexibility' for CBA. Weight is a function of the garment and gravity alone: the other two requirements include factors such as the range of movement of the unarmoured wearer. Whether both levels of requirements are equal depends on the nature of the system. Hence, there is a need to understand the measurement of ergonomic effectiveness.

The main drawback of wearer trials is that they can be costly – requiring full prototypes and wearers' time – and are therefore only carried out as a penultimate stage in the development process. A tool used by the French military on their FELIN soldier modernisation program (Rouger, 1999) is reverse biomechanical simulation (ESI Group, 2000) to predict the effect of new rifles on soldiers' muscular workload. Such techniques could be extended for use with personal armour to assess fatigue. Moreover, novel development of this software using muscle efficiencies has the potential to introduce biothermodynamical models that predict overheating.

The objectives of Chapter 8 are therefore to (i) assess the operation of the Mk 5 EOD Suit visor demister, (ii) describe the choice of measures for ergonomic evaluation and (iii) discuss novel assessment tools.

4.6 SYNTHESIS & OPTIMISATION OF PERSONAL ARMOUR DESIGN

The designer must make predictions in order to create personal armour. He or she needs to assess whether or not a particular design will be an improvement on existing solutions. This takes a relative comparison of present and proposed armours in envisaged scenarios. If the designer is proactive rather than reactive, the setting may not even exist yet. The choices for assessing armour proposals are to (i) extrapolate historical trends into the uncertain future, (ii) build real garments and test them in representative scenarios and (iii) construct a simulation of the system. Each has its own strengths and weaknesses.

Historical information such as casualty data from previous conflicts (Beyer, 1962) is a statement of the past. This is particularly true for casualty data because modelling the human body via mechanical surrogates, animal specimens and cadavers is notoriously difficult (NATO, 2003). However, it is unwise to blindly extrapolate historical trends too far into the future.

The production of real armour for test in representative scenarios can be conducted at various system levels as described for ergonomics evaluation in Chapter 3. Limited aspects of the system may be tested in isolation such as measuring the areal density (weight per unit area) (Tobin, 1985) and cost per unit area (Roberson, 1995) of material required to defeat a specified threat. However, issues outside the test may prove to be important such the combination of threats, their likelihood of occurring or the effect of each extra kilogram of armour on the wearer. This approach represents a basic tool for selection or an input into a larger model of the system.

The most advanced method of testing is to use complete garments in scenarios as close to reality as is feasible. For example, complete EOD suits (Gotts, 2000, Bass & Davis, 2004) have been used in explosive trials rather than just subject to FSPs (NATO, 1996). Human surrogates can be used to synthesise the wearer in order to assess incapacitation. Finished garments can then be worn in wearer trials (Edwards & Tobin, 1990a, Kistemaker et al., 2004) to test their influence on the ability to complete tasks. The major drawback of real world testing is that it is expensive and time consuming to conduct, particularly for the more detailed tests. EOD suits currently cost thousands of GB pounds: cadavers cannot be readily obtained in the UK. Hence, real world testing of complete garments is best used for proving designs rather than developing a wide range of novel options.

A simulation of the system in a virtual environment has the potential to allow a greater number of designs to be considered before prototypes are built. The most advanced simulations of personal armour design are military casualty reduction analysis programs such as the UK's CASPER (Hunting Engineering, 1999) and the USA's ComputerMan (Saucier & Kash, 1994), which is used in the Netherlands (Verhagen et al., 2002). Currently, CASPER is used to calculate the probability of incapacitation for garments of different weights (Gotts, 1999). However, Gotts only uses CASPER to estimate the benefit of armour and not the ergonomic penalty: the weight constraint is calculated separately. Moreover, the rejection of unsuitable designs must be carried out visually because threats are considered separately and incapacitation rather than protection is used as the benefit. This is because it is not possible to say whether a degree of incapacitation is acceptable without knowing how serious the threat is in the first place.

There is potential to demonstrate how casualty reduction analysis software can be extended to synthesise enough of the personal armour design system so that unsuitable designs are deselected automatically; leaving a range of reasonable solutions that can be considered for construction as a real prototype. This has the potential to be the world's first integrated personal armour design simulation.

The objectives of Chapter 9 are therefore to (i) develop methods of trading-off the benefits and penalties of any personal armour solution and (ii) demonstrate the adaptation of casualty reduction software, so that those that do not offer the 'best possible protection' can be deselected.

4.7 DISCUSSION

The selection of research aims is based on the fact that currently it is not possible to solve a systems approach to personal armour design absolutely. This is because complexity reduces the power of deterministic analysis. Therefore, the systems approach in this thesis is one of a series of aims at different system levels – likened to a portfolio of 'pictures' with various scales – designed to enhance the current state of knowledge. Each research aim has a level of fidelity that depends upon the hierarchical level. The reader must understand that conclusions at high levels are most appropriate as qualitative trends and relative answers. As the system level decreases, the conclusions become closer to quantitative absolutes. For example, the assessment of secondary fragmentation is a definition of probabilities; the synthesis of personal armour design is a demonstration of a new method. Consequently, the method used to assess secondary fragmentation is not the essence of the answer to that research aim; neither are numerical examples the essence of the synthesis of personal armour design.

4.8 CONCLUSIONS

1. The objectives of Chapter 5 are to define the system boundary, levels of control, hierarchy and emergent properties. This highlights two subsystems for the primary benefit and penalty of armour for further analysis in Chapters 6 & 8. It also provides a framework for synthesis of the system in Chapter 9.

2. The objectives of Chapter 6 are to refine the protection subsystem, propose a measure for assessing this benefit of armour and then demonstrate this knowledge. The definition of this subsystem provides a framework for the inclusion of the single example in Chapter 7.

3. The aim of Chapter 7 is to support the development of the Lightweight Combat EOD Suit by assessing the threat of secondary fragmentation from AP blast mines. The objectives are to estimate the likelihood of being hit, defeating armour and hurt when no armour is available. These can be understood as inputs to the protection subsystem.

4. The objectives of Chapter 8 are to demonstrate ergonomic design using visor demister operation for the Mk 5 EOD Suit as an example, discuss measures of ergonomic effectiveness and propose a novel method of calculating this.

5. The aim of Chapter 9 is to unify as much of the knowledge gained in Chapters 6 and 8 as is feasible in the time available in order to synthesise personal armour design in a computer simulation. The objectives are therefore to develop methods of trading-off the benefits and penalties of armour and demonstrate the adaptation of casualty reduction analysis software, so that only solutions that offer 'the best possible protection' are left to prototype.

6. An additional aim of this thesis is to support, where appropriate, the development of the Lightweight Combat EOD Suit and Mk 5 EOD Suit.

7. The research aims form a series of snapshots at different system levels rather than a continuum of smoothly interlinking topics. Conclusions drawn about them must be appropriate to the system level involved.

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CHAPTER 5: ELICITATION OF PERSONAL ARMOUR DESIGN (SYSTEM)

5.1 INTRODUCTION

5.1.1 Aim

To construct a model of the personal armour design system based on existing solutions in order to improve individual, man-portable, defensive coverings within the context in which they are to be used (Chapter 1.1). This provides a holistic framework to deconstruct the system in Chapters 6 to 8 and synthesize it in Chapter 9.

5.1.2 Objectives

- Identify an appropriate boundary for the personal armour design system,
- Define the level of control that the designer has over the various inputs,
- Elicit the hierarchy of containing systems and subsystems,
- Deduce the emergent properties that are traded-off in order to select solutions.

5.1.3 Background

Systems theory (Section 2.4.2) allows the designer to consider personal armour as a product of interacting components and influences. It is the trade off between these constituent parts that defines solutions such as garments or shields. This chapter elicits a model of the personal armour design system by comparing historical solutions.

The influences on personal armour design have changed considerably during the course of history. The threat has transformed from hand-thrown spears to high-velocity bullets and beyond, while materials technology has evolved from leather to ceramics. Nevertheless, the fundamental challenges of personal armour design have not changed in over 5000 years. It is assumed that although the solutions are different, the underlying system remains the same.

History offers a variety of personal armour solutions to study. A selection is used to provide 'snapshots' of the system, rather than a complete chronicle of personal armour design. These are compared to build up a model of the underlying system. A potential weakness of this comparative approach is that of bias towards the Western world due to the availability of information. Considering a wider variety of Indo-European armours would not necessarily lessen such a weakness because these have been influenced by each other. To counter this, the system elicited from Indo-European armour of the period before 1500 AD is compared with garments and shields found in Mexico at the moment of the Spanish arrival as documented in the Codex Mendoza (Anonymous, 1541-1542). These can be considered to have evolved separately and provide verification of the system model.

5.2 THEORY

5.2.1 The personal armour design system as a template

The basic premise for this chapter is that a system is an underlying pattern: different personal armour solutions are the result of different contexts being applied to the same template. This is akin to Plato's theory of 'forms' (360 BC); that everything has a fundamental pattern associated with it. If one compares a multitude of personal armour solutions, the things that stay constant are part of the system while the things that differ are part of the individual solutions. For example, some armour covers the head and others cover the torso so helmets and vests are different representations of the system. However, all armour has material that covers a region of the body: this relationship is thus part of the system.

5.2.2 Assumptions

The following assumptions are made in order to define the system.

1. All the solutions considered in this chapter are rational: they all meet the requirements of armour designs to a greater or lesser extent. This is acceptable because all the solutions are established, as far as is possible, to have been used in practice. The assumption implies that all the designers endeavoured to balance the same system.

2. The designer is concerned with 'short to medium' timescales – the lifespan of a single product. This bounds the influences that must be considered in the system to those that have immediate or 'near future' effect. A longer term view would recognise that improvements in armour design affect the development of new threats. It would also

include the influence of materials usage on the environment. Both of these influences are therefore not included in this model. This assumption is deemed to be reasonable because personal armour design is a relatively small scale operation compared to major manufacturing and wider defence industries so has a weaker influence on the environment. It also has greater priority for fighting the next battle than future ones. Hence, the personal armour design system is bounded in time with respect to the lifespan of a garment.

5.3 METHOD

The method is to contrast selected Indo-European personal armour solutions over the period to 1500 AD and draw conclusions on the common features they exhibit. The deductions are compared with Mesoamerican personal armour of circa 1541 – which evolved separately. Features that still remain common are then defined as part of an underlying system. These are arranged into a pattern that fits the solutions.

5.4 RESULTS

5.4.1 Description of Indo-European personal armour (pre-1500 AD)

The earliest known items of personal armour are shields. A wall painting from Egypt in Tomb 100 at Hierakonpolis (25°05'N 32°47'E) shows that shields were known around 3500 BC (Figure 5.1). The shield bearer is shown defending himself from an attacker armed with at least a spear. This type of defensive armament is distinguished by the ability of the combatant to manoeuvre it in response to changes in the direction of the threat. It is often positioned with one arm while the other is used to hold an offensive weapon. The skill of the fighter is to choose tactics that put the shield between him and the threat during a defensive manoeuvre. Therefore, shields only cover a proportion of the body at any one time, e.g. the back of the combatant is not covered. They must also be light enough and the wearer strong enough to maintain the level of protection throughout the battle.

The other type of personal armour is body armour, which includes items of clothing such as helmets and protective vests. These are characterised by the fact that they remain approximately stationary with respect to the area of the body they are designed to cover. This is useful if the direction of the threat is not known such as in open combat with multiple attackers. The earliest pictorial evidence of body armour comes from the Sumerians in Mesopotamia around 2500 BC. The Standard of Ur (Hackett, 1989) (Figure 5.2) depicts foot soldiers wearing helmets or caps, lamellar skirts and studded cloaks. This type of protection is worn so that both arms are available to bear arms. A larger area of coverage than for a shield is required because body armour is not moved relative to the wearer. However, extra weight is less of a burden since its weight acts closer to the wearer's centre of gravity. A key difference in the requirements of both types of personal armour is that body armour must be flexible enough so that the person can move.

Figure 5.1: Portion of a wall-painting at Hierakonpolis circa 3500 BC (Tomb 100 at 25°05'N 32°47'E after Woosnam-Savage & Hall, 2001)

Figure 5.2: Portion of the Standard of Ur circa 2500 BC (British Museum, WA 121201 after Hackett, 1989)

The 'Vulture' Stele of Eannatum I from Sumer (Figure 5.3) shows that the type and level of personal armour that is chosen depends on the tactics employed. A fragment of the stele depicts both heavy and light infantrymen – all with helmets. The former are a rank of spearmen in formation behind a row of shields. Their role is relatively immobile and therefore vulnerable. A wall of heavy-duty shields is a sensible level of protection for these troops. The latter hold a long spear and a battle-axe. These men find protection by being fast and therefore difficult to hit. Hence, they carry no shields or cloaks and wear only a skirt and helmet.

Figure 5.3: Portion of the Vulture Stele circa 2500 BC (Louvre AO 16 IO9 after Louvre, 2005)

Flexible yet light personal armour was achieved first with natural materials such as leather. Later, metallic armours were developed using small plates or lamellae that have a degree of movement relative to each other. This type of garment manufactured from bronze was available in Egypt around 1500 BC. A bas relief from around 700 BC (Horsfall, 2000) (Figure 5.4) illustrates an Assyrian cavalryman using a short-sleeved vest of lamellar armour in addition to a helmet. This combination offers protection for the areas of the body with the most grievous consequences of injury, i.e. excluding the arms and legs. The flexibility of the vest was sufficient for the highly mobile task of riding on horseback. Moreover, it is interesting to note that the development of metallic armours coincides with increasing threats which, by the time of Assyrian dominance, included composite bows. Thus, armour technology – both materials and constructions – and threat development are key drivers of new designs.

Refinement of metallic armour continued in classical Greece with the development of rigid but perfectly fitting breastplates. An illustration of a muscle cuirass is presented on an amphora from 530 BC (Bull, 1991) (Figure 5.5). It depicts the legend of Achilles killing Penthesilea, Queen of the Amazons. Herodotus (440 BC) describes the historical use of a similar item of armour: "Immediately the Athenians rushed upon Masistius as he lay… At first, however, they were not able to take his life; for his armour hindered them. He had on a breastplate formed of golden scales, with a scarlet tunic covering it. Thus the blows, all falling upon his breastplate, took no effect, till one of the soldiers, perceiving the reason, drove his weapon into his eye and so slew him." Single-piece armours have fewer weak points than those with many joints. However, they were probably tailored to the wearer and thus valuable property of high-ranking individuals. This demonstrates that there is a relationship between the protection offered by and financial cost of personal armour.

Figure 5.4: Portion of a bas relief of an Assyrian cavalryman circa 700 BC (British Museum, WA 118907 after Horsfall, 2000)

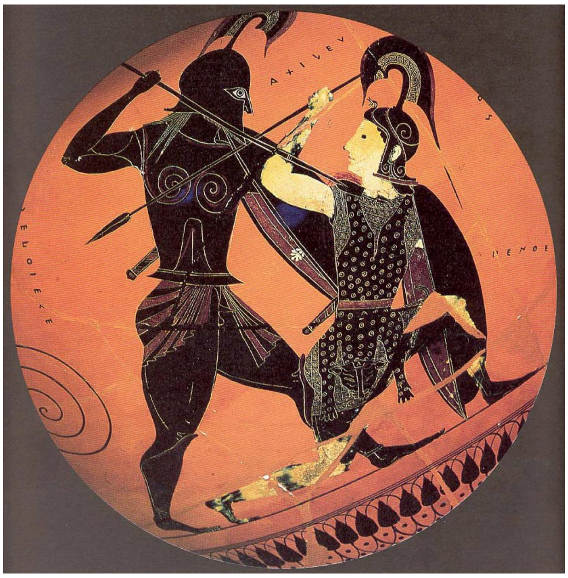


Figure 5.5: Image of Achilles killing Penthesilea from an amphora circa 530 BC (The British Museum, BM 210 after Bull, 1991)

In addition to the breastplate, Achilles is shown wearing a full-face, 'Corinthian' helmet and a circular shield supported on his left arm. His helmet has a greater area of coverage than Penthesilea's open-faced one. However, it has the disadvantages of limiting the fighter's hearing and, if the helmet is not a good fit, eyesight. The development of supporting shields, in this case along the length of the arm, allows the fighter to provide a stronger more stable defence than simple hand-held shields. Alternatively, the same protection could be offered for a longer period of time. These changes support the idea that armour design is evolutionary with successful designs depending, not only on their financial cost and ability to protect, but also the ergonomic penalties that are incurred.

Hoplite warfare dominated Greece during the 7th to 5th centuries BC. This was characterised by well-drilled infantry fighting in phalanx formation using a round shield, spear and thrusting sword but often no body armour except a helmet. Thucydides (431 BC) records the defeat of the Spartan Army during the Peloponnesian War. "[The Athenian army] being lightly equipped, and easily getting the start in their flight, from the difficult and rugged nature of the ground, in an island hitherto desert, over which the Lacedaemonians could not pursue them with their heavy armour…After this skirmishing had lasted some little while, the Lacedaemonians became unable to dash out with the same rapidity as before upon the points attacked, and the light troops finding that they now fought with less vigour, became more confident… The shouting accompanying their onset confounded the Lacedaemonians, unaccustomed to this mode of fighting; dust rose from the newly burnt wood, and it was impossible to see in front of one with the arrows and stones flying through clouds of dust from the hands of numerous assailants. The Lacedaemonians had now to sustain a rude conflict; their caps would not keep out the arrows, darts had broken off in the armour of the wounded, while they themselves were helpless for offence, being prevented from using their eyes to see what was before them, and unable to hear the words of command for the hubbub raised by the enemy; danger encompassed them on every side, and there was no hope of any means of defence or safety." This shows that protection and ergonomic penalties such as reduced mobility, fatigue and sensory impairment are dependent on the battle environment as well as the armour.

After the era of classical Greece, Roman power flourished until its empire stretched from north Europe to northern Africa. Expansion gave the Romans the chance to assimilate ideas from the people they conquered as well as to develop their own technology. Lamellar (lorica squamata), mail (lorica hamata), and segmented (known from the Renaissance period as 'lorica segmentata') body armour in addition to pictorial evidence of muscle cuirasses used by the

Romans have been found (Robinson, 1975). Roman lamellar garments and cuirasses resemble designs discussed earlier in this chapter.

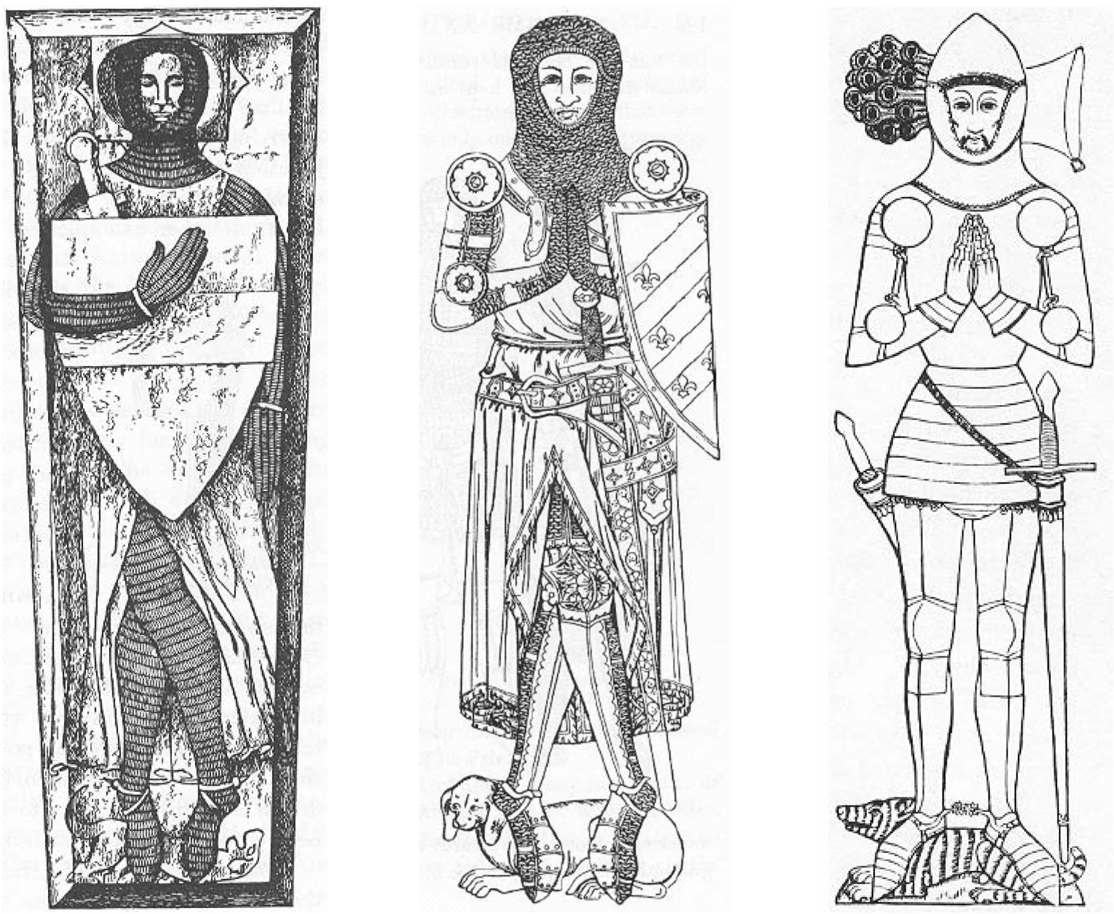
Probably the best known items of Roman personal armour are the 'coolus' helmet, lorica segmentata and the curved, rectangular shield (scutum) as depicted on Trajan's Column (Hackett, 1989) (Figure 5.6). The coolus helmet has a neck guard, shaped flaps protect to the cheeks and a stunted peak that strengthens the brow. Reinforcing armour in key areas rather than across the whole surface reduces the overall weight Articulating the flaps means than the helmet can fit a range of head shapes more comfortably than a solid construction. This style is a significant advance from single-piece designs such as the aforementioned 'Corinthian' helmet. Articulation of plate armour is the key behind the lorica segmentata. The joints offer flexibility of movement and the garment is laced up to accommodate a variety of wearers. It allowed the Romans to gain the economic benefits of mass production. This was of particular importance because in the 1st century AD the financial burden of armour was transferred from the soldier to the state. Plutarch (75 AD) describes the petition of Caius Grachhus to the popular assembly, "Of the laws which he now proposed… another was concerning the common soldiers, that they should be clothed at the public charge, without any diminution of their pay." This demonstrates that armour designers must consider the full target audience; from the biggest, fastest, strongest person to the smallest, slowest, weakest one. Moreover, the designer must understand how individual soldiers work together. This point is illustrated in the shape and usage of the scutum. The curve of the shield increases the area of coverage for the individual soldier, while the rectangular shape minimises any gaps between people in a defensive wall. Hence, armour is used to benefit the whole security force, not just the individual.

Armour designs hardly changed during the first millennium AD. The Norman period provides the next example since it is documented relatively well. The Bayeux Tapestry (Bull, 1991) (Figure 5.7) records the Norman conquest of Saxon England, which culminated in the Battle of Hastings in 1066. The Norman knights are depicted wearing conical helmets with nasal bars, knee-length mail suits (hauberks) and 'kite' shields. These were designed to offer a degree of protection from lances, arrows, maces and axes. The hauberk is part of a continuing trend to increase the area of protection of body armour. It covers from the neck to the elbows and knees. The tactics results in a fluid but chaotic battle whereby threats can come from any direction and thus body armour becomes a priority. Nevertheless, the well-trained soldier is able to position his shield to best effect. The kite shape represents a stage in the reduction of the size of the shield. It is broadest near the top so that it guards the upper part of the body. The shield tapers down to a point so that only the left leg is covered. This is in marked contrast to the superior coverage of the Roman shield design discussed earlier. Moreover, archers are shown wearing no such armour since their task is to remain at a range where they have a relatively low likelihood of being struck. This stage in history is part of a continuing trend to concentrate armour, weapons and training for close combat in a relatively few individuals. Hence, the objective of battle – and therefore a purpose of armour – is to win with as few friendly casualties as possible.

Figure 5.6: Portion of Trajan's Column circa 100AD (Trajan's Forum, Rome after Hackett, 1989)

Figure 5.7: Portion of the Bayeux Tapestry circa 1066-1077 AD
(Centre Guillaume le Conquérant, Rue de Nesmond, Bayeux, France after Crack, 1998)

The trend of increasing body armour for a decreasing number of combatants reached an apogee via full body suits. These were first made of mail and then reinforced with plates, until a full plate suit became the norm for knights (see Figures 5.8a, b & c which cover 1227-1407 AD). During this period, arms such as swords, axes and maces were superseded by missile weapons. In particular, the crossbow was recognised as a military weapon by the close of the twelfth century AD (Ashdown, 1995). Its combined armour-piercing potential and accuracy was a strong influence in the gradual increase of garment weight and rigidity. Additional design changes include the development of deflection surfaces, to encourage blows to glance off, and fluting to provide extra stiffness (see Figure 5.8c). This progress continues to follow the fundamental, primary driver behind the design of armour – threat evolution as discussed in section 5.3.2.



Figures 5.8: 3 Stages of armour suits (a) Sir John de Bitton, Bitton Church, Somersetshire, 1227 AD, (b) Sir --- de Fitzralph, Pebmarsh Church, Essex, c. 1320 (c) Lord Robert Ferrers of Chartley, Merevale Abbey Church, Warwickshire, 1407 AD (after Ashdown, 1995)

5.4.2 Description of Mesoamerican armour (circa 1541 AD)

The preceding examples of personal armour focus on designs produced by Indo-European influenced cultures. It can be argued that since these two streams of human thought influenced each other that common themes in such designs are unsurprising. However, if one studies cultures that evolved more or less separately then similar patterns are highlighted. The development of Mesoamerican personal armour is an example. It evolved independently of European influence until the Spanish arrived. The Codex Mendoza (Anonymous, 1541-1542), as documented by Berdan & Anawalt (1997), records in hieroglyphs the conquests of the rulers of Tenochtitlán (today known as Mexico City) and the daily lives from cradle to grave of its people. It was compiled at the request of the Spanish King Charles V around 20 years after the Spanish defeat of the Mexica. Therefore, it provides a remarkable view of Mesoamerican warriors, their weapons and their armour before the influence of European ideas. A key feature is the lack of metal in their military technology. Folio 2r of the Codex Mendoza depicts four warriors clad in ichcahuipilli and carrying round ihuitetyo shields (Figure 5.9). This type of body armour was made from thick, quilted cotton: unspun fibre stitched between layers of cloth. It was designed to offer protection to torso, abdomen and pelvis from weapons such as the obsidian edged club and wooden battle stick as shown in Figure 5.9. Moreover, it provided excellent protection against arrows as testified in a Spanish annotation next to a drawing of an ichcahuipilli in the Codex Vaticanus A (Anonymous, 1570-1589) as cited by Berdan & Anawalt (1997). This declares that the Spaniards adopted this garment because arrows that could pierce the strongest mail and some cuirasses could not penetrate the "escauiples." Despite the lack of metallic armour, many similarities may be drawn between Mesoamerican and designs from the rest of the world. Their areas of coverage, division between body armour and shield, balance between protection and ergonomic characteristics are common features. The most striking difference is the absence of helmets.

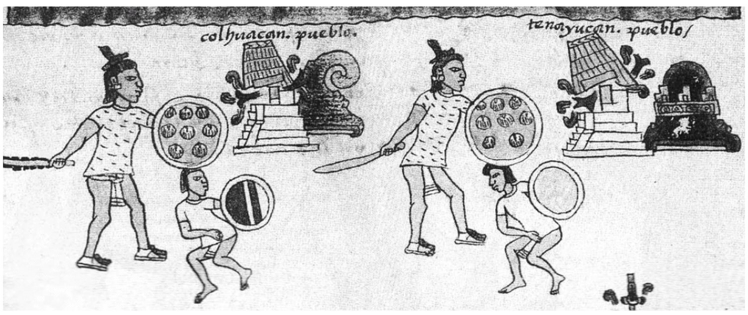


Figure 5.9: Extract from Folio 2r of the Codex Mendoza
(Bodleian Library 3134 after Berdan & Anawalt, 1997) circa 1541 AD

5.4.3 Common features of Indo-European and Mesoamerican armour (pre-1500 AD)

The following table (5.1) presents the common features of Indo-European personal armour (pre-1500 AD) that are not refuted through comparison with a Mesoamerican solution from circa 1541 AD. It is listed in terms of relationships between system components; with examples presented for each.

component 1	**relationship**	**component 2**	**examples (*ceteris paribus*)**
armour	is influenced by	threat	stronger armour for greater threats
armour	is influenced by	environment	less armour for hotter climates
armour	is influenced by	materials technology	armour can only be made of what is available
armour	is influenced by	wearer	armour designed to fit wearer
armour	is influenced by	task	lighter armour for faster action
armour	consists of	materials	what it is made of
armour	consists of	construction	how it is put together
armour	consists of	coverage	size and position in relation to the wearer
armour	consists of	don/doff	state of wearing/not wearing a garment
armour	influences	protection	armour saves lives
armour	influences	ergonomic effectiveness	armour slows the wearer
armour	influences	financial cost effectiveness	armour costs money
protection	is influenced by	threat	more threats increases danger
protection	is influenced by	environment	less shielding increases danger
protection	is influenced by	wearer	smaller men are less exposed
protection	is influenced by	task	a greater range decreases danger
protection	is influenced by	ergonomic effectiveness	slower men are in danger longer
protection	influences	tactical effectiveness	protection increases the number of people are available
protection	influences	ergonomic effectiveness	protection can reduce fear
protection	influences	financial cost effectiveness	damaged armour is replaced
ergonomic effectiveness	is influenced by	threat	greater danger increases fear
ergonomic effectiveness	is influenced by	environment	rougher terrain slows the wearer
ergonomic effectiveness	is influenced by	wearer	swifter men move faster
ergonomic effectiveness	is influenced by	task	easier tasks are carried out faster
ergonomic effectiveness	influences	tactical success	tasks completed well do not have to be repeated so often
financial cost effectiveness	is influenced by	threat	stronger armour costs more
financial cost effectiveness	is influenced by	environment	harsher environments wear out armour quicker
financial cost effectiveness	is influenced by	wearer	bigger men need bigger, more expensive armour
financial cost effectiveness	is influenced by	task	rougher usage wears armour quicker
financial cost effectiveness	influences	strategic success	Money used cannot be spent on alternative resources
tactical success	influences	strategic effectiveness	Small wins lead to big wins

Table 5.1: Common features of Indo-European and Mesoamerican armour (pre-1500 AD)

An influence diagram is presented in Figure 5.10 of the system model of personal armour design and related links.

5.4.4 System model

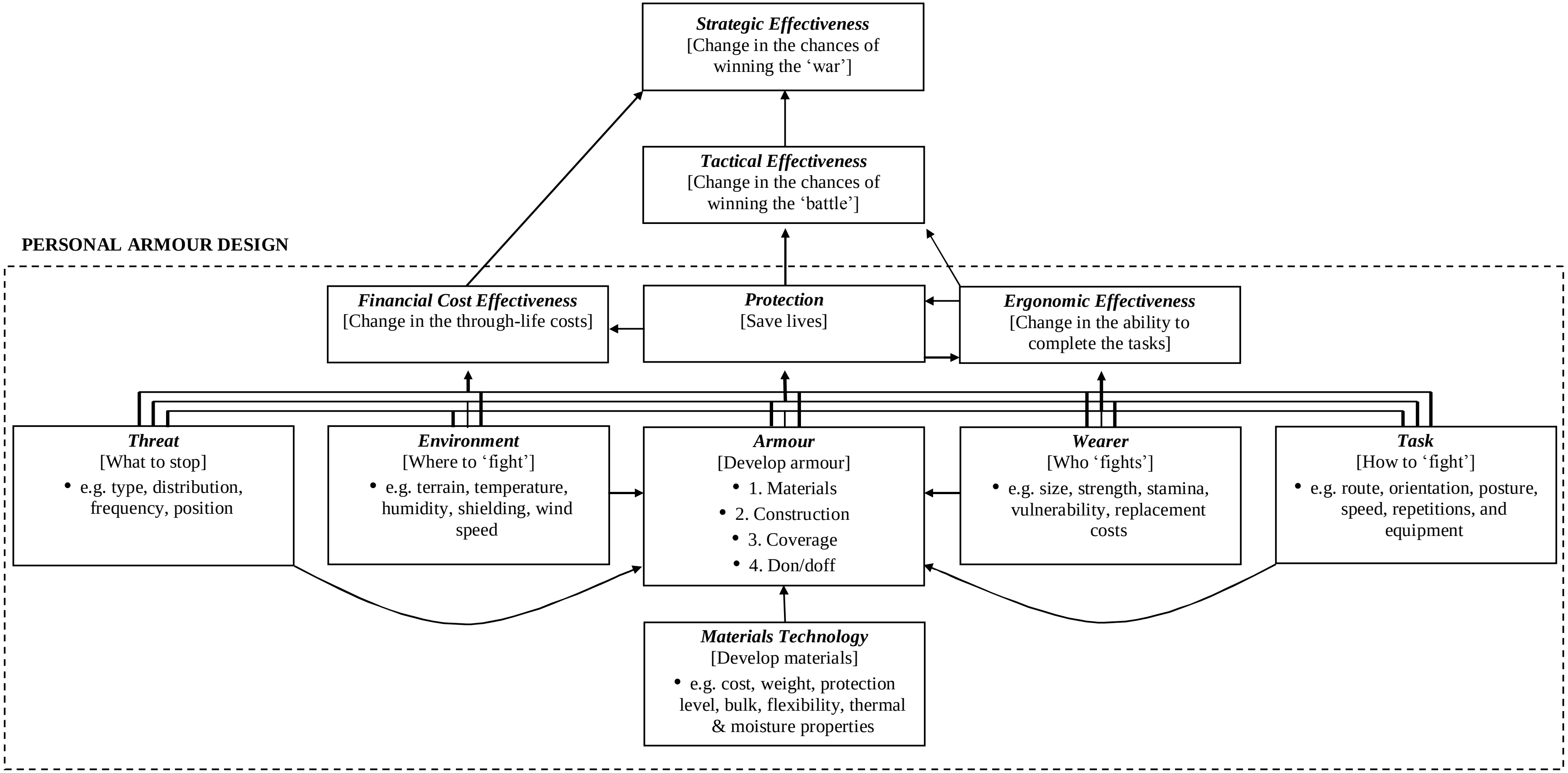


Figure 5.10: System model produced from common features of Indo-European and Mesoamerican armour (pre-1500 AD)

5.5 DISCUSSION

5.5.1 System model limitations

All human observation is prone to bias of the observer; this chapter is no exception. Deductions made from historical and modern armour and the assumptions above are based upon the author's viewpoint. Justifications for this approach are (i) that the author has spent the last six years working closely with the UK's Defence Logistics Organisation and communicating with the international personal armour community and (ii) the reader's own interpretation of the facts. The best system model that can come out of this chapter is always going to be a reasoned argument to form a picture of the system. It is intended simply to be a framework upon which to combine and refine knowledge of personal armour design within this thesis and without.

5.5.2 The personal armour design system boundary

A system boundary has length, breadth and depth as described in Section 2.4.2. Assumption 2 in this chapter limits the length of the system boundary to the lifecycle of a single garment. The breadth is the threat, environment, armour, wearer and task as illustrated in Figure 5.10. The depth of the system boundary is from the emergent properties down to the sub-subsystem level of factors such as materials properties.

Tactical effectiveness and strategic effectiveness are outside of the system boundary and are grouped into the heading of 'command.' It is therefore not for the armour designer to say what the system is used for, only that it has emergent properties which make it more or less effective at contributing to tactical and strategic goals.

5.5.3 The designer's level of control

The designer has absolute control – within the bounds of possibility – over the choices that define the garment or shield [armour], can suggest how it is used [task] but has no or very little influence over where it is used [environment], against what weapons [threat], who uses it [wearer], what technology is available to make it [materials technology] and for what purpose [command]. This gives three levels of control for the boundary around the system (Figure 5.11). This is reasonable if one considers personal armour designers to be customer-focussed or subservient to military and security force goals. The issue of lack of control of the availability of materials technology is reasonable too when considered with Assumption 2: materials research tends to be a separate, on-going activity aside from the design of specific garments.

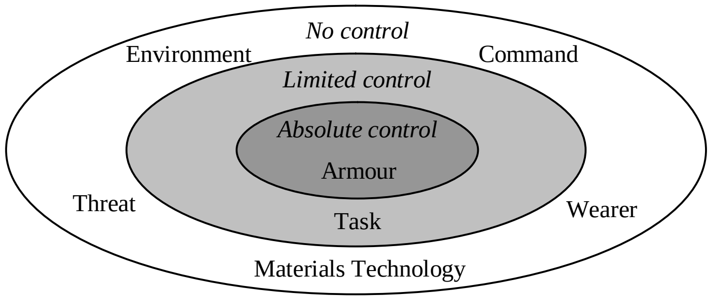


Figure 5.11: Levels of control of the personal armour designer during the lifespan of a product

5.5.4 The system hierarchy

The pinnacle of the hierarchy lies outside of the personal armour design system boundary at the suprasystem level. This is reasonable considering that the final choice – of which solution to select – rests with the customer or commander and not the designer.

The system level is based around the combination of threat, environment, armour, wearer and task, from which three main properties emerge of protection, ergonomic effectiveness and financial cost. These can be broken down into three distinct but linked subsystems. The sub-subsystem level is based around partial inputs to the components of threat, environment, armour, wearer and task.

5.5.5 The emergent properties

The three emergent properties of protection, ergonomic effectiveness and financial cost effectiveness are distinct in that they produce separate positive or negative effects. Protection is the positive benefit of wearing armour and this is reflected in Figure 5.10: it directly influences the goal of tactical effectiveness and the emergent properties of ergonomic and financial cost effectiveness. Ergonomic effectiveness is the main constraint to personal armour design. This is illustrated by its direct link to tactical effectiveness and protection. Financial cost effectiveness is the lesser of the constraints because it only influences strategic success directly.

5.6 CONCLUSIONS

1 The system model outlined in this chapter is the product of the author's viewpoint and is subject to his bias. Nevertheless, it provides a holistic framework to deconstruct the system in Chapters 6 to 8 and synthesize it in Chapter 9

2 The system boundary is for the lifecycle of a single garment; for the combination of threat, environment, armour, wearer and task; and from the emergent properties to sub-subsystems such as materials properties.

3 The commander and purchaser sit outside the system boundary and are the users of the capability that is enhanced or degraded by personal armour.

4 The designer has absolute control over the choice of materials, construction and coverage of armour to achieve the desired emergent properties. He or she has limited control of the way that armour is used.

5 The system is divided into three subsystems based around the emergent properties of protection, ergonomic effectiveness and financial cost effectiveness. The first is the positive benefit of armour; the second is the main constraint; the third is a lesser constraint.

5.7 RESEARCH RECOMMENDATIONS

It is recommended that the system model is refined and developed; not only to look at a wider, deeper, longer system boundary but also to join up the constituent components more rigorously. The viewpoints of a wide range of people should be combined to make a new model more thorough.

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CHAPTER 6: MEASUREMENT & MODELLING OF PROTECTION (SUBSYSTEM)

6.1 INTRODUCTION

6.1.1 Aims

To refine the protection subsystem elicited in Chapter 5, improve the methods and tools used to assess this primary benefit of personal armour and support the development of the Lightweight Combat EOD Suit (Chapter 2.2.3).

6.1.2 Objectives

- Describe the protection subsystem including feedback in appropriate detail,
- Identify a suitable measure of protection effectiveness,
- Demonstrate the novel use of casualty reduction analysis software to assess protection,
- Assess the protection offered by the Lightweight Combat EOD Suit as an example.

6.1.3 Background

Protection is the *raison d'être* of practical personal armour. This stems from the very definition of personal armour as outlined at the start of Chapter 1. All other design requirements are constraints in the pursuit of the ideal of absolute protection. It is therefore vital that the designer has a full and accurate understanding of this subsystem of personal armour. This chapter expands our concept of protection, and then provides a suitable measure of this benefit of armour. It highlights the importance of proper accounting for the sources of protection. These points are used to develop a generic model of the subsystem that applies to any personal armour design, whether for military or police use and whatever the threat involved. A casualty reduction analysis program named CASPER (Hunting Engineering, 1999) is then used to demonstrate that existing tools can be developed to answer two key questions. Firstly, how can the task be made safer? Secondly, how useful is armour if the task is defined? This links to the notion in Chapter 5 that the designer has absolute control of the armour and limited control on its use (Figure 5.11)

Two conference papers have been presented (Couldrick & Gotts, 2000, Couldrick et al., 2002) that introduce the main body of ideas developed in this chapter and Chapter 9. Supporting material is contained in Appendix B and Couldrick et al (2002) is given in Appendix D.11.
The numerical simulations in this chapter focus on the assessment of protection for explosive ordnance disposal (EOD) personnel. This choice of subject is due to the development of the Lightweight Combat EOD Suit (Gotts, 2000), which was designed by DLO DC R&PS during this course of study. Typical threats that the user may encounter range from anti-personnel mines and grenades up to 1000kg bombs. No personal armour system can offer complete protection against all these threats. Instead, the Lightweight Combat EOD Suit reduces the number of penetrating fragments and slows down the rest in order to lessen the severity of injuries. This is in marked contrast to police bullet-proof jackets, which are designed to stop, absolutely, stated ballistic threats for a limited area of the body. Nevertheless, the lessons learned can be applied to any item of personal armour in any scenario.

It is important to note that armour itself can cause potentially fatal incapacitation. A common example is heat strain brought on through the use of NBC clothing (Kelm, 1996). In this case, it is the burden of a garment that leads to the wearer overheating. This type of incapacitation is *not* included in the protection subsystem since it is a design constraint and not an objective. The ability to complete the task is explored in Chapter 8.

6.2 THEORY

6.2.1 Protection as a key user requirement

Protection is *the* key user requirement of personal armour. It is the defensive side of survivability once the task is defined: the offensive side is to use a weapon to kill or disable the enemy before they can hurt the combatant. The need to survive comes from both group and individual motives. A group needs its members to survive so that, in the short-term, its goals can be achieved – in essence to win the battle and therefore the war. Incapacitated combatants cannot fight and reduce the availability of those who attend to the dead and wounded. In the longer term, there are political, moral and financial obligations upon the group to support their dead and wounded. War pensions, hospital care, disability payments, lack of political support are just a handful of the penalties incurred by the military when troops are injured or killed. For the individual, survival is one of – if not *the* – strongest drives in any human being.

Despite the great desire for protection, the risk of incapacitation cannot be eliminated altogether. Military armour such as fragmentation vests, countermine suits and EOD suits can always be overmatched. They are designed to offer a degree of – rather than absolute – protection from threats that include grenades, mines and shells. These may produce a variety of fragments and blast waves that cannot be stopped using current materials without imposing unacceptable ergonomic and financial burdens. Even police armour that is deemed to be bullet-proof only covers a fraction of the body. Hence, protection is a relative measure that depends on the scenarios involved. It can be achieved by removing the person from danger or increasing the protection level of armour. The danger is reduced first e.g. by staying out of the direct line-of-fire. If they must still work in dangerous scenarios then armour can be worn to reduce the chance of injury or death. A measure of protection effectiveness is needed that differentiates between protection due to armour and that due to alternative sources such as choosing a safer route or adopting more stealthy tactics. The assumptions upon which this view of the protection subsystem is based are stated first.

6.2.2 Assumptions

There are many viewpoints from which to define a system. It is therefore necessary to state the assumptions that must hold true for this picture of the protection subsystem to be acceptable.

1. The wearer does not care what part of their body is injured, only that they are incapacitated to a greater or lesser degree. It does not matter whether a person is killed due to a head or chest injury: they are still dead. Nevertheless, the probability of incapacitation (P_i) depends on factors such as threat position, wearer posture and vulnerability. This means that different protection levels may be required for different body regions. Therefore, protection must be calculated across the whole body.

2. Multiple threats and injury mechanisms may occur in the same body region. For example, a variety of fragment sizes and a blast wave may interact with the wearer's torso. The armour designer must balance protection based on the relative likelihood of each threat type. Hence, it is necessary to assess protection within – as well as between – body regions.

3. Protection is time dependent because armour can be donned or doffed and shields can be picked up or put down. It may be preferable to wear a lightweight garment

constantly rather than heavier but more threat-resistant armour intermittently or vice versa. Therefore, the designer should calculate protection for the duration of a task or mission.

These assumptions are the foundations of protection assessment for personal armour. A suitable measure of protection effectiveness is now required. The following section examines the weaknesses of existing measures and proposes a novel one.

6.2.3 Measures of protection effectiveness

Protection is the difference in incapacitation between the states of being unarmoured and armoured. There are a variety of measures that armour designers have used to describe protection. Some are genuine – though limited – measures of protection. Others only gauge the degree of incapacitation.

Ballistic protection is often assessed using the V_{50} or V_0 for specified projectiles: the minimum velocity at which 50% or 0% of impacts will penetrate an armour, (Kneubuehl, 1996, Tobin, 1998). The latter measure is analogous to the energy levels in stab-resistant body armour standards (Pettit & Croft, 1999). They describe the protection offered against an individual impact in a specified orientation to the armour as a binary state: either the threat is stopped or not. There is no analysis of the effect on the human body if the garment is overmatched. Moreover, there is no assessment of the likelihood of being hit in the first place. They are genuine measures of protection but are limited to the provisions that any penetration causes incapacitation, only one type of threat occurs and it is guaranteed to hit the armour.

A more complete assessment is achieved using casualty reduction analysis. This divides protection assessment into two parts. Susceptibility describes the probability of being hit by a projectile (P_{hit}). Vulnerability details the probability of being incapacitated given that a hit has occurred ($P_{i|hit}$). The product of these two quantities is P_i which is a measure of incapacitation, not protection.

A common measure used in casualty reduction analysis (Reches, 1978) is vulnerable area (A_V), which is the product of the target presented area (A_P) and $P_{i|hit}$. This is related to the previous measure of incapacitation because A_P can be viewed as a proxy for P_{hit} for a randomly

distributed threat: the greater the presented area, the greater the susceptibility. Hence, vulnerable area is a proxy for P_i and is not a measure of protection.
Vulnerable area can be averaged for threats at different ranges and angles around the body to give the mean area of effectiveness (*MAE*). However, this too is a proxy for P_i and not a measure of protection.

The computational casualty reduction analysis program used by DLO R&PS (CASPER) has a further measure named the percentage reduction in casualties (*%CasRed*) as given in Equation 6.1. It is an estimate of the expected reduction in casualties in any scenario, due to wearing armour. However, it assumes that the armour is hit so does not account for the full effect of the scenario. A garment that stops 50% of a threat and is guaranteed to be hit (Scenario A) will have the same *%CasRed* as if it has a 50% chance of being hit (Scenario B), even though in the former case it saves twice as many people. Table 6.1 illustrates this example in more detail. *%CasRed* is therefore a limited measure of protection effectiveness for the armour designer.

$$\%CasRed = \left(1 - \frac{P_{i\ armour}}{P_{i\ unprotected}}\right) \times 100 \tag{6.1}$$

A measure of protection effectiveness is proposed by the author (Couldrick & Gotts, 2000) that is based on the likelihood of saving people. It compares the expected incapacitation with and without a protective garment. The usefulness factor (*UF*) combines the likelihood of being hit by an injurious threat and the estimated reduction in casualties due to wearing armour, for a given incapacitation criterion such as death. Transforming Equation 6.2 shows that *UF* is the difference between P_i for an unprotected and armoured person for a given incapacitation criterion. $P_{i\ unprotected}$ rather than P_{hit} is used because the former excludes the susceptibility to non-injurious threats. The beauty of *UF* is that it only rates the protection afforded by armour. If a task is safe then there is no need for armour and the protection is zero. If a garment is guaranteed to be overmatched then there is no protection and *UF* is zero. Protection is only available if a person is likely to be hit *and* saved from injury. Thus, *the usefulness factor is the reduction in probability of incapacitation due to wearing armour within the context of use*.

$$\begin{aligned} UF &= P_{i\ unprotected} \times \%CasRed \div 100 \\ &= P_{i\ unprotected} - P_{i\ armour} \\ &= P_{i\ unarmoured} - P_{i\ armoured} \end{aligned} \tag{6.2}$$

Table 6.1 illustrates the difference between *%CasRed* and *UF* for three scenarios (A, B and C). One type of armour stops 50% of the threat in A and B, while another type stops 90% in C. The likelihood of being hit is 100% in A, and 50% in B and C. $P_{i\ unarmoured}$ is the combination of $P_{i|hit}$ and P_{hit}. $P_{i\ armoured}$ equals P_{hit} if it is assumed that all hits on an unarmoured person cause incapacitation. *%CasRed* and *UF* are calculated using Equations 6.1 and 6.2. The expected number of people saved who would otherwise be incapacitated, E_{saves}, per 1000 people equals 1000*($P_{i\ unarmoured} - P_{i\ armoured}$). Hence, *UF* tracks the number of people protected while *%CasRed* does not. *%CasRed* suggests that the armour in scenario C is best because all threats are stopped. *UF* proposes that its benefit is negated by a lower likelihood of being hit: money would be best spent on armour for scenario A in order to save more people.

Scenario	$P_{i\|hit}$	P_{hit}	$P_{i\ unamoured}$	$P_{i\ armoured}$	*%CasRed*	*UF*	E_{saves} per 1000 people
A	0.5	1	1	0.5	50	0.5	500
B	0.5	0.5	0.5	0.25	50	0.25	250
C	0.1	0.5	0.5	0.05	90	0.45	450

Table 6.1: Comparison of *%CasRed* and *UF* for three theoretical scenarios

Despite the clarity of *UF* as a single measure of protection effectiveness, it has one weakness. It, like other methods that use P_i, requires an incapacitation category such as death: either the person fits into this class or not. *UF* can be used to quantify the reduction in numbers of casualties likely to receive a particular degree of injury. A typical question is "How many soldiers are left to fight a battle?" An alternative question seeks to qualify the decrease in incapacitation. For example, "What reduction in the type of injury is a soldier likely to receive?" Just because a person is not killed, it does not follow that they are unharmed. Qualification of protection is the rationale behind the trauma scores summarised (Davis & Neades, 2002) and outlined in Chapter 3. The major problem with qualification is that the armour designer cannot prescribe one level of incapacitation over another. For certain people, it is preferable to save lives at any cost. Others prefer death over risking fellow comrades-in-arms only to have major, permanent disablement and be dependent on intensive care. The solution to providing quantitative and qualitative measures of protection effectiveness is to provide values of *UF* for several incapacitation criteria. The designer is then in the position to inform an armour user of the likely protection. It is then up to the user to define what level of incapacitation is acceptable: it is their informed risk to take.

6.2.4 Five-stage definition of the protection subsystem

It is proposed that the protection subsystem leads to *UF* being estimated in five stages that are henceforward named *occurrence*, *incidence*, *resistance*, *incapacitation* and *protection* (Figure 6.1). 'Occurrence' defines the likelihood of each particular event (threat type, range, orientation, etc.) existing at a given time. It is a product of the threat and task, such as the density of and route through a minefield. Additionally, occurrence is affected by the stealth of an individual; such as a well camouflaged soldier who exposes himself to less gunfire than an overt patrol. Alternatively, offensive tactics can be used to eliminate the threat first.

'Incidence' describes the likelihood of particular threat characteristics striking a person. It depends on the threat distribution relative to them. Initially, this is defined by the dispersal of e.g. fragments or blast waves in an unrestricted environment as found from arena trials or free-field blast wave propagation theory. Modifications then occur due to interactions with the environment such as the effects of shielding, air drag and surface reflections. If armour is hit, its ability to stop the threat must be evaluated.

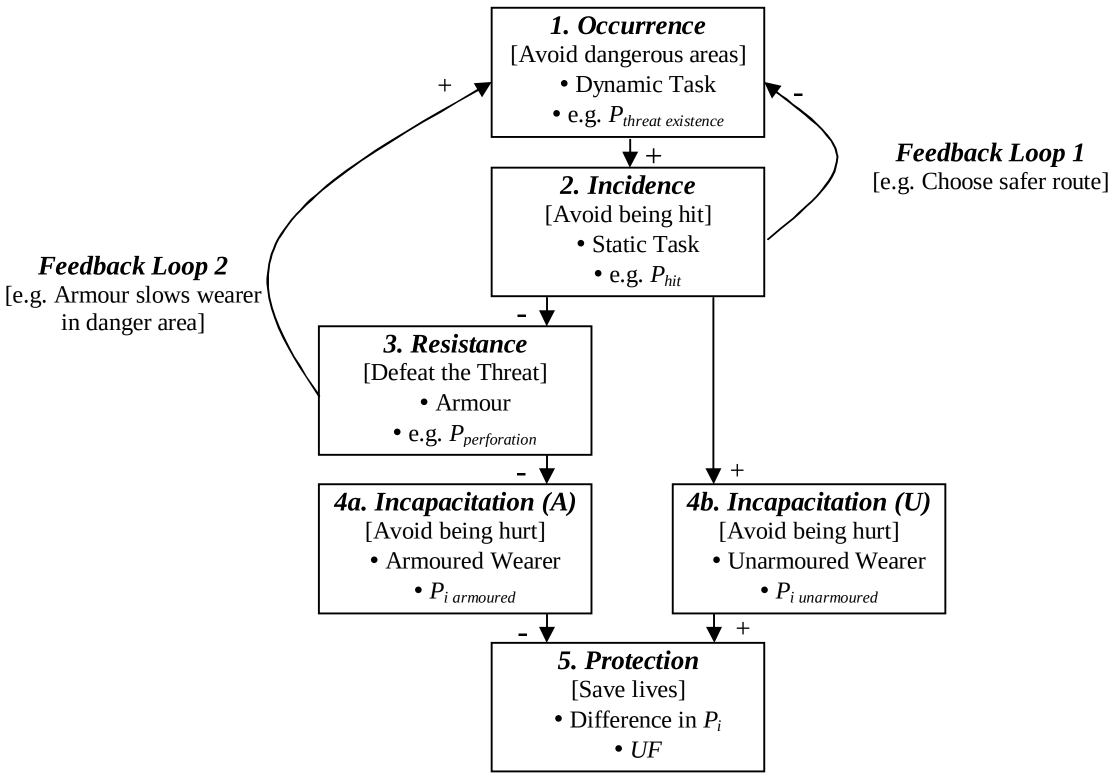


Figure 6.1: Five-stage estimation of protection

Occurrence and incidence are sometimes lumped together under the heading of 'susceptibility.' This is described (Ball & Calvano, 1994) as an "inability to avoid" and is expressed using the probability of being hit, P_{hit}. However, subdividing susceptibility enables the armour designer to make recommendations about safer tactics.

'Resistance' defines the residual properties at the back face of the garment. The choice of which attributes to use depends on the type of threat. For example, a description of the perforation by fragments should include their masses, residual velocities and probabilities of defeating the armour (Kneubuehl, 1996, Tobin, 1998). This allows the designer to link the models of armour resistance and incapacitation.

P_i is calculated from a model of wearer 'incapacitation' due to the threat behind the garment, e.g. for fragments (Kokinakis & Sperrazza, 1965) and blast (Bowen et al., 1968). Incapacitation models such as these may be derived from a variety of sources including accident reports, biomechanical simulations and cadaver or animal experiments. A great deal of subjective interpretation by medical experts is often required to assess the results. Moreover, assumptions must be made about the availability of casualty care. An untreated casualty may die from wounds that are recoverable in first world hospitals. Nevertheless, it is important that all the stages link together regardless of whether they are modelled or measured from experiments. It is then possible to estimate P_i for each threat and area of the body, regardless of the injury mechanism, subject to a common incapacitation criterion such as death. However, the assumptions listed earlier imply that it does not matter how or where a person is killed: they are still dead. Binomial combination is used to obtain P_i for the whole body from the separate threats to individual body regions as demonstrated in Equation 6.3.

$$(1 - P_{i\,total}) = (1 - P_{i\,fragment,head}).(1 - P_{i\,blast,torso})\ldots \tag{6.3}$$

$$P_i(0 < t < T) = \frac{\int_0^T P_i(t).dt}{T} \tag{6.4}$$

P_i $(0<t<T)$ = probability of incapacitation occurring during task
$P_i(t)$ = probability of incapacitation occurring at time t
T = task duration

Moreover, it does not matter when an incapacitation occurs. It should be noted that, since the task is dynamic, P_i is a function of time. If the task is assumed to finish when $P_i(t)$ is approximately 0, then Equation 6.4 is used.

Resistance and incapacitation can be lumped together under the heading of 'vulnerability.' This is described (Ball & Calvano, 1994) as an "inability to withstand" and is expressed using the probability of incapacitation given a hit, $P_{i|hit}$. However, subdividing vulnerability enables the armour designer to estimate the effects with and without armour.

Finally, 'protection' is estimated with the usefulness factor as given in Equation 6.2. This is the benefit of protection that is traded off against ergonomic and financial penalties in Chapter 8.

CASPER estimates P_i with and without ballistic armour, for a static event with a probability of occurrence of 1 (i.e. stages two to four of the five-stage model). If a sequence of simulations – each with an associated probability of occurrence – is combined then a dynamic task can be represented. It is used for military personal armour design and could be used for police ballistic vests.

Police – in contrast with military – personal armour is designed to stop a threat absolutely for a limited area of the body as outlined in the various test standards. Protection is restricted to the regions most likely to be hit by a threat that can cause serious injury, i.e. excluding the arms and legs. This is a reasonable assumption if the threat is targeted such as a knife or bullet, or if any injury to the arms or legs is deemed acceptable. In these cases a set of threats is assumed to occur absolutely and be distributed so that the armour is hit with specific properties. This means that stages one and two of the calculation of P_i are ignored. Moreover, the choice of bullets or knives is such that they can be stopped 'absolutely.' For example, a ballistic vest is designed to stop all of the specified bullets, whilst making blunt trauma unlikely. Alternatively, stab resistant armour is accepted only if the penetration of specified knife threats is limited to a distance that is deemed unlikely to cause serious injury. This means that an incapacitation model in stage four is redundant. These assumptions simplify the design down to a single go-no go decision: does the garment stop the specified threat? Hence, current police body armour is a simplified case of the same design system as military personal armour.

If the simplifying assumptions behind police armour change then there will be a direct need to use the five stage model. For example, if a proportion of bullets used against the police were armour-piercing would ballistic vests still be useful? There is also another, indirect reason for all armour designers to consider the implications of a systems view of the five stage model: there are two feedback loops that affect the person's chances of being incapacitated.

The first feedback loop is negative and shows that it is possible to make tasks safer by choosing paths that offer the lowest likelihood of being hit. This point is demonstrated by in Section 6.2.6 for an EOD operator approaching unexploded munitions. If information about the position and orientation of the device are known, it is possible to minimise P_i for the unarmoured person. This is equivalent to minimising the probability of being hit by anything likely to be injurious.

The second feedback loop is also negative (the combination of pluses and minuses around the loop are negative) and highlights the threat increase (occurrence) as a result of wearing armour. For example, it has been demonstrated (Ashby et al., 2004) that infantry soldiers wearing heavy, more threat-resistant armour can be more likely to die than those wearing lighter, less threat-resistant garments. This is due to slow-moving infantrymen being exposed in a danger zone for longer than faster ones. The implications of the two feedback loops in optimising personal armour for protection are demonstrated in the following section.

6.2.5 Feedback in the protection subsystem

The two feedback loops in the protection subsystem affect the usefulness of armour. This phenomenon is demonstrated using the trends from the following theoretical EOD scenario.

1. An EOD operator is assumed to inspect a fictional, cylindrical fragmentation device. The threat has a vertical axis of symmetry and is the same height as the person. Hence, it is reasonable to approximate $P_{i|occurrence}(x)$ as inversely proportional to the horizontal range (x). Air drag is neglected.
2. The threat is set to operate on a random fuse. Therefore, the probability that the device detonates is constant throughout the task. The probability of this happening ($P_{occurrence}(t)$) is 0.5. This is an exponentially distributed hazard function as described by Knezevic (1993).
3. The task is to approach to within 1m of the device from outside its lethal range (R); inspect it for 10 seconds; withdraw to safety. The unarmoured operator moves at $2ms^{-1}$. The lethal range is defined as x when $P_i(x) = 0.01$ for the unarmoured, standing person.

4. The wearer can make the task safer by adopting a crouching posture. This has the effect of reducing his or her exposed surface area by 15%. Therefore, $P_{i|occurrence}(x)$ for a crouched person is approximated as 15% less than for an exposed one.
5. The effects of armour are assumed to be twofold. Firstly, enough fragments are stopped or slowed to reduce $P_{i|occurrence}(x)$ by 20%. Secondly, the ergonomic penalty is that the armoured operator moves at $1.5ms^{-1}$.

This scenario is illustrated in the following graphs. Figure 6.2 shows $P_{i|occurrence}(x)$, which is the probability of incapacitation given that the device detonates while the operator is at *x*. The four alternatives reflect the possible combinations of reducing incidence (adopting a safer posture) or increasing resistance (wearing armour). *R* is found to be 50m by combining $P_{i|occurrence}(x)$ and $P_{occurrence}(t)$.

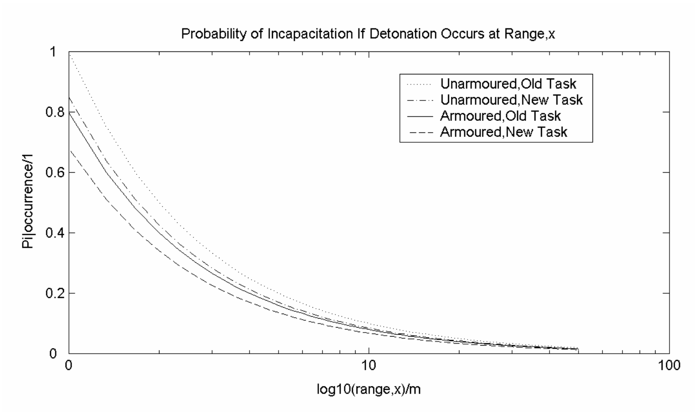


Figure 6.2: $P_{i|occurrence}(x)$ for a theoretical EOD inspection

Once *R* and the operator's velocity (*x'(t)*) is known the task (*x(t)*) is defined, as shown in Figure 6.3. This demonstrates that an armoured person spends longer in a danger zone than an unarmoured one. Although both people finish the task at the same range, their end time (*T*) is 75.33 or 59s respectively.

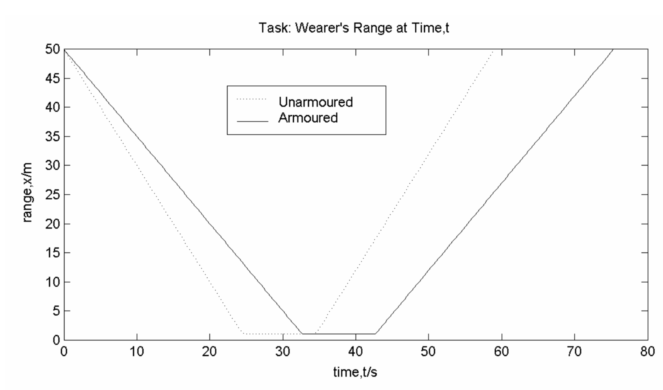


Figure 6.3: Task *x(t)* for a theoretical EOD inspection

$P_{i|occurrence}(x)$, $x(t)$ and $P_{occurrence}(t)$ are combined to give $P_i(t)$. This is illustrated in Figure 6.4. P_i for the entire duration of the task is then derived using Equation 6.4.

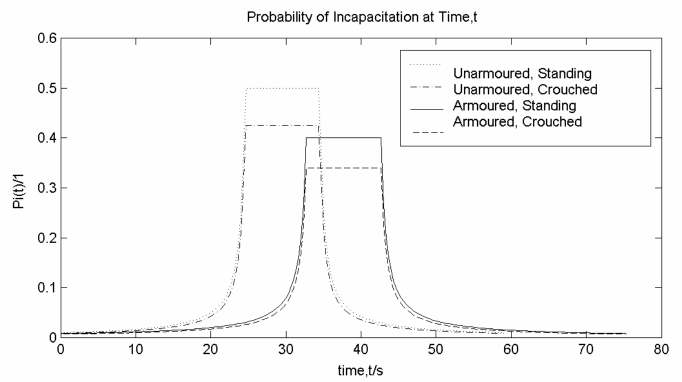


Figure 6.4: $P_i(t)$ for a theoretical EOD inspection

The computed values of P_i for the four alternatives are given in Table 6.2. These provide four different measures of *UF*. The first value (*i*) is obtained if the task remains unchanged. It ignores the benefit that can be achieved by making the task safer. Hence, this measure is an overestimate of the true usefulness of armour. It should be discarded. Likewise, value *ii* is an overestimate because it includes the advantage of altering the operator's posture. It should be rejected too. Value *iii* is an underestimate because it reflects the wearer choosing to make their task more hazardous than necessary. It should also be discarded. The final value (*iv*) is the true usefulness of armour. Therefore the definition of *UF is refined as: the reduction in P_i for a given incapacitation criterion, after any reasonable reduction in incidence, due to wearing armour within the context of use.*

Number	**Unarmoured**		**Armoured**		**UF**
	Task	$P_{i\ unarmoured}$	**Task**	$P_{i\ armoured}$	
i.	Standing	0.118	Standing	0.081	0.037
ii.	Standing	0.118	Crouched	0.069	0.049
iii.	Crouched	0.100	Standing	0.081	0.019
iv.	Crouched	0.100	Crouched	0.069	0.031

Table 6.2: Alternative measures of protection for a theoretical EOD inspection

This example demonstrates the importance of a systems approach to personal armour design. If either feedback loop is ignored then the estimated usefulness of – and therefore the estimated number of lives saved by – armour is wrong. Therefore, the armour designer must not only provide the operational analyst with a 'best estimate' of protection but also iterate the design process to improve the estimate.

6.2.6 Making tasks safer – the approach plot

CASPER estimates the chance of becoming a casualty, seriously injured or killed at a specific location. Then it calculates the percentage of people that are likely to move to a lower incapacitation category as a result of wearing armour. Developing these outputs helps answer two key questions. Which route is the safest way to approach or pass a particular threat? If the approach route is defined, how useful is the armour?

Choosing the safest route to a threat is not simply a matter of taking a bird's eye view of the fragment distribution. It depends on where fragments are likely to hit the body; e.g. arms are less vulnerable than the torso. It also depends on the position of the person and their orientation to the threat. The *Approach Plot* (Figure 6.5) gives a better representation. In this case, it is a polar graph of the probability of an EOD operator being incapacitated at a given range and angle around the threat ($P_i(r, \vartheta)$). A value of 'zero' indicates that the person would not be incapacitated: 'one' means that the person definitely would be. The EOD operator can then choose the most feasible route with the lowest P_i.

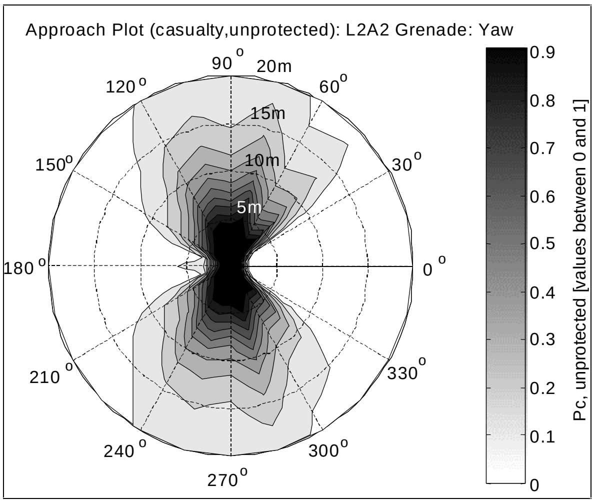


Figure 6.5: Example of an approach plot

An approach plot must specify the incapacitation category and level of armour that is under consideration. In this thesis, the probability of an unprotected person being a casualty is presented ($P_{c\ unprotected}$). This shows the chance of any fragment – regardless of size or velocity – hitting the person. Although large, fast fragments are usually more penetrative than small, slow ones; this type of plot still shows the safest routes where the probability of being hit is zero, regardless of incapacitation category or protection level.

Approach plots can be mapped in alternative coordinate systems with multiple threats to make other tasks safer. This idea becomes increasingly useful as sensors improve, particularly in the age of battlefield digitisation. Furthermore, an approach plot enables routes to be optimised that minimise P_i for the duration of the task.

6.2.7 Mapping the benefit of armour – zone of usefulness

Once the EOD operator in the previous section has chosen a route, the next decision is whether or not to wear armour. For armour to be useful, it must (a) be hit and (b) stop/sufficiently slow down the fragment. This means that there are two extremes where armour is not very useful. It is unlikely to be hit if it is too far from the threat. It is unlikely to offer much protection if it is too close to the threat. However, in-between these two extremes there is a *Zone of Usefulness* diagram (Figure 6.6). In this case, it is a polar graph of the *Usefulness Factor* (Equation 6.2) for a specified incapacitation category at a given position around the threat ($UF(r, \vartheta)$). The usefulness factor combines the likelihood of being hit and the estimated reduction in casualties due to wearing armour. Regions are shown on the plot where wearing armour is likely or unlikely be beneficial.

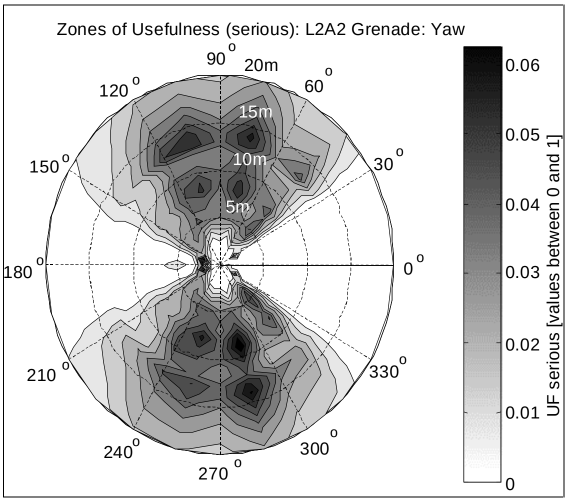


Figure 6.6: Example of a zone of usefulness plot

This provides an initial tool to help EOD personnel decide where to wear armour. Dynamic maps offer the potential to assist them with the decision of when to don or doff a protective garment.

6.3 METHOD

6.3.1 Simulation parameters

CASPER (Hunting Engineering, 1999) is used to estimate P_i for armoured and unarmoured states and *%CasRed* if armour is worn. These are calculated for the three summarised Kokinakis-Sperrazza criteria (Waldon et al., 1969) of 'casualty', 'serious' and 'lethal' for a person approaching the threat in a crouched position, with the stationary threat at ground level. Six threats are used: L2A2 grenade, No. 36 Mills grenade, M18A1 Claymore anti-personnel mine, HB876 area denial mine, BL755 sub-munition and 105mm artillery shell. Each device can be rotated around three axes in planes corresponding to its 'yaw', 'pitch' and 'roll'. In this chapter, the most likely orientation for each threat is selected to demonstrate the idea.

Simulations are run for the two variables of range (r) and angle (ϑ) around each threat. These are calculated at every 1/20th of the maximum range and 15º. CASPER calculates P_i and *%CasRed* for all ranges, armour states and incapacitation categories in a single run. However, it is designed to move the threat around the man rather than vice versa, so that simulations must be carried out for each 15º increment (i.e. 24 runs) around each threat. A summary of the simulation variables is given in Table 6.3.

Threat	Azimuth / º	Elevation / º	Range r / m
M18A1 Claymore mine		--- not available ---	
L2A2 grenade	0 → 345 (i = 15)	0	0 →20 (i = 1)
No. 36 Mills grenade	0 → 345 (i = 15)	0	0 →20 (i = 1)
HB876 area denial mine	0	270	0 →30 (i = 1.5)
BL755 sub-munition	0	90	0 →30 (i = 1.5)
105mm shell	0 → 345 (i = 15)	0	0 →50 (i = 2.5)

i = increment

Table 6.3: Simulation variables

6.3.2 Target definition

The person is represented in the standard crouched position (NATO, 1995) facing the threat (Figure 6.7). They are covered by a model of the Lightweight Combat EOD Suit and helmet, which is a modular design. Geometric and materials data are stored in separate files for the torso, pelvis, upper arms, lower arms, upper legs, lower legs and helmet/visor. This enables parts to be removed for separate analysis.

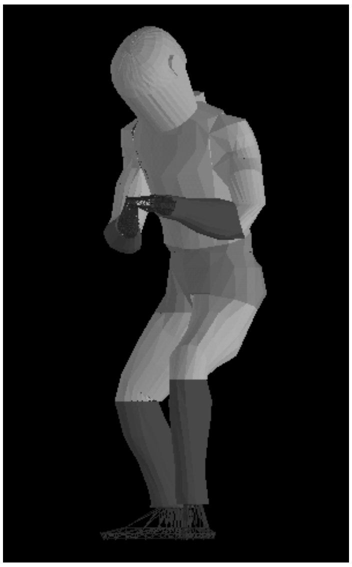


Figure 6.7: CASPER (Hunting Engineering, 1999) model of a crouched person wearing the Lightweight Combat EOD Suit

A summary table of the geometry and materials files is given in Table 6.4. This shows that standard armour geometries as specified in CASPER are used except for the visor, which is tapered at the sides to represent the final suit design. A description of this modification and the CASPER representation of this part (number 7010) is given in Appendix B.1. The numerical materials information given in Table 6.5 shows that the front and rear ceramic plates are assumed to be impenetrable (level 1). The limb armour is modelled at level 2 and the helmet and jacket are given as level 3.

Item	Parts	Material	Description	Filenames	Source files	Modified geometry?
Man	as given	---	crouched	crouched.*	crouched.*	no
Helmet	7001, 7002, 7005	3	helmet	cachelm.*	cbt-eod.*	no
	7010	3	tapered visor			yes
Armour	8001 – 8008	3	vest & collar	cacarm.*	cba-eod.*	no
	8009, 8010	1	plate inserts			no
Upper arms	8111 – 8114 8121 – 8124	2	upper arm armour	cacarmup.*	arm-upr.*	no
Lower arms	8211 – 8214 8215 8221 – 8224	2	lower arm armour	cacarmlo.*	arm-lwr.*	no
Pelvis	8301	2	pelvis armour	cacpelv.*	pelvis.*	no
Upper legs	8411 – 8414 8421 – 8424	2	upper leg armour	caclegup.*	leg-upr.*	no
Lower legs	8511 – 8516, 8521 – 8526	2	lower leg armour	cacleglo.*	leg-lwr.*	no

Table 6.4: Target components

Material level 2		Material level 3	
Fragment mass, *m* / g	**V_0 / ms^{-1}**	**Fragment mass, *m* / g**	**V_0 / ms^{-1}**
0.13	725.0	0.13	797.5
0.25	651.5	0.25	716.7
1.10	500.0	1.10	550.0
4.06	397.0	4.06	436.9

Table 6.5: Level 2 & 3 material properties (level 1 = impenetrable)

6.3.3 Threat definition

Six potential threats are modelled to provide a range of fragment types (Table 6.6). Each threat is stationary and at ground level.

Threat	Fragment Type	Range Limit/ m
M18A1 Claymore AP mine	Pre-formed, directional	50
No. 36 Mills grenade	Small, random	20
L2A2 grenade	Small, pre-formed	20
HB876 area denial mine	Misznay-Schardein	30
BL755 sub-munition	Pre-formed, axisymmetric	30
105mm artillery shell	Large, random	50

Table 6.6: Threats to the Lightweight Combat EOD Suit

Most of the threats are already defined in the CASPER threat database (Riach, 1997). However, the Claymore mine and BL755 sub-munition are added using available data of fragment masses, distributions, materials, area coefficients, ricochet angles and drag coefficients. A letter from Hunting Engineering (Collinge, 2000) which designed the BL755 is used to create the weapon file given in a separate, classified appendix to this thesis (Couldrick, 2004).

6.3.4 Data transformation

CASPER calculates the values of P_i for each incapacitation category and protection level. From this, the percentage reductions in casualties are computed. The numerical values of these outputs are presented in a number of text files: one for each threat and 15º increment. A spreadsheet (Excel®†) is used to collate the files for a particular threat and orientation, and remove extraneous information. It is also used to compare the input information in each file

† Microsoft, USA. http://www.microsoft.com

with a standard template to reduce the chance of human error. This output is summarised in Appendix B.2.

When the data are reduced to a matrix of angles, ranges and probabilities they are exported to a maths package (Matlab®‡) to be converted into a graphical output. A polar filled contour map is produced that displays the probability or usefulness as a pseudo-colour scale against r and ϑ. The Matlab M-file that is used to produce the plots is presented in Appendix B.3.

6.4 RESULTS

6.4.1 M18A1 Claymore anti-personnel mine

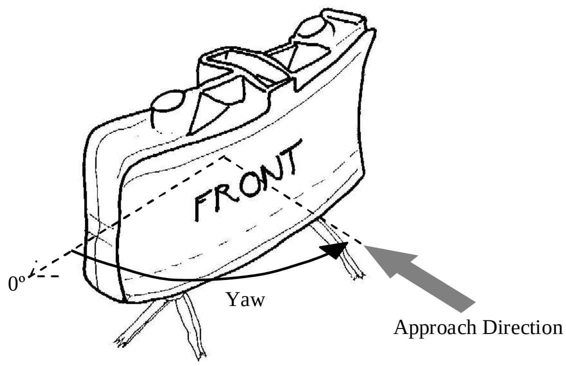


Figure 6.8: M18A1 Claymore anti-personnel mine orientation

The distribution of fragments from a Claymore AP mine (Figure 6.8) could not be modelled easily within CASPER because it is not axisymmetric. Getting the fragment density correct around the 0º axis and using two impenetrable shields as a filter to remove extra fragments could produce an approximate model. However, this is not deemed necessary for this thesis.

‡ MathWorks, USA. http://www.mathworks.com

6.4.2 L2A2 grenade

The approach plot (Figure 6.10a) shows that the safest routes to an L2A2 grenade lying on its side (Figure 6.9) are from the base and the fuse end. A reasoned interpretation of the results must be made because CASPER does not include the fuse fragments. Given the choice, it would be most sensible to approach such a device from the base end (180º yaw).

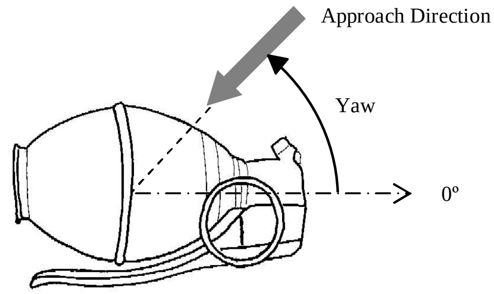
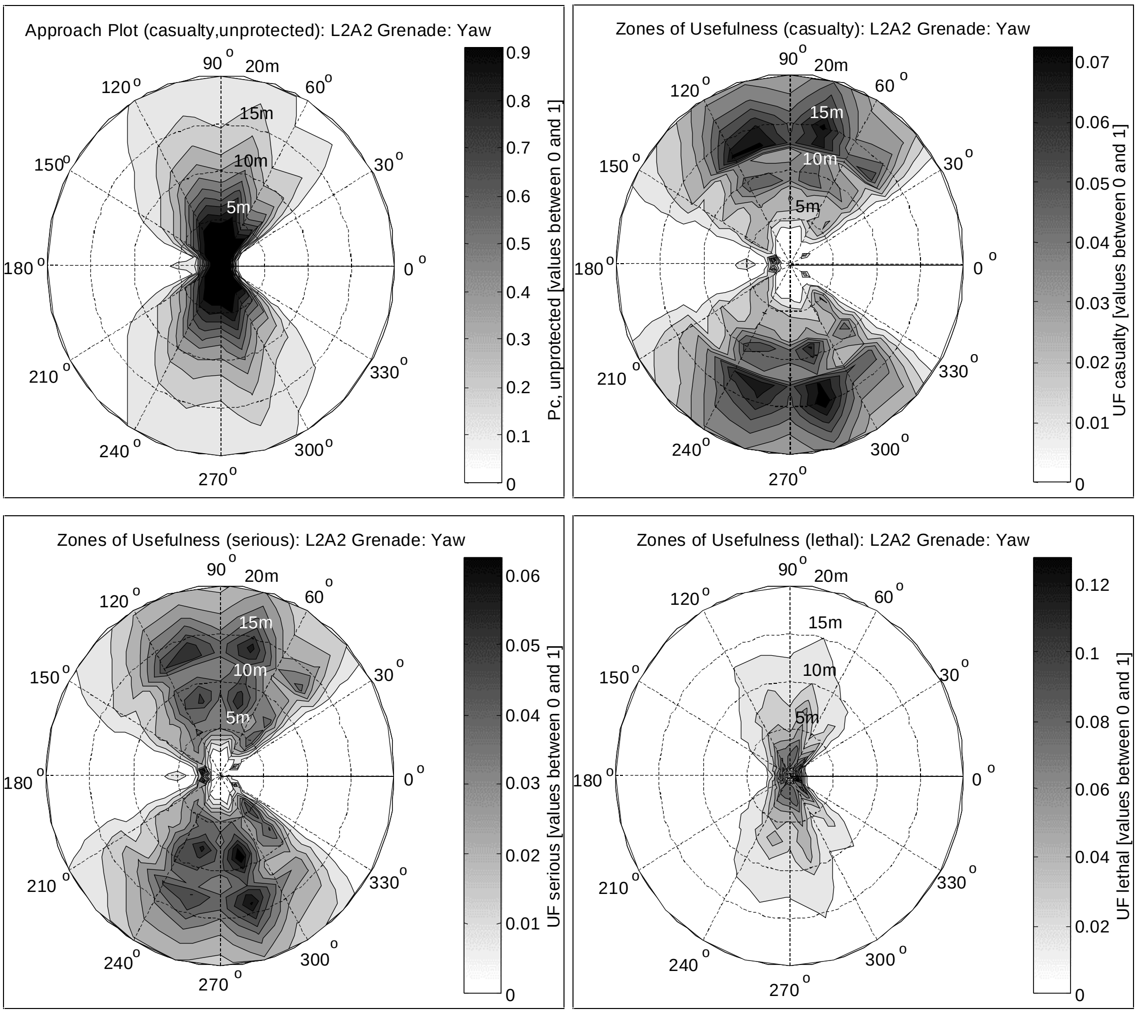


Figure 6.9: L2A2 grenade orientation

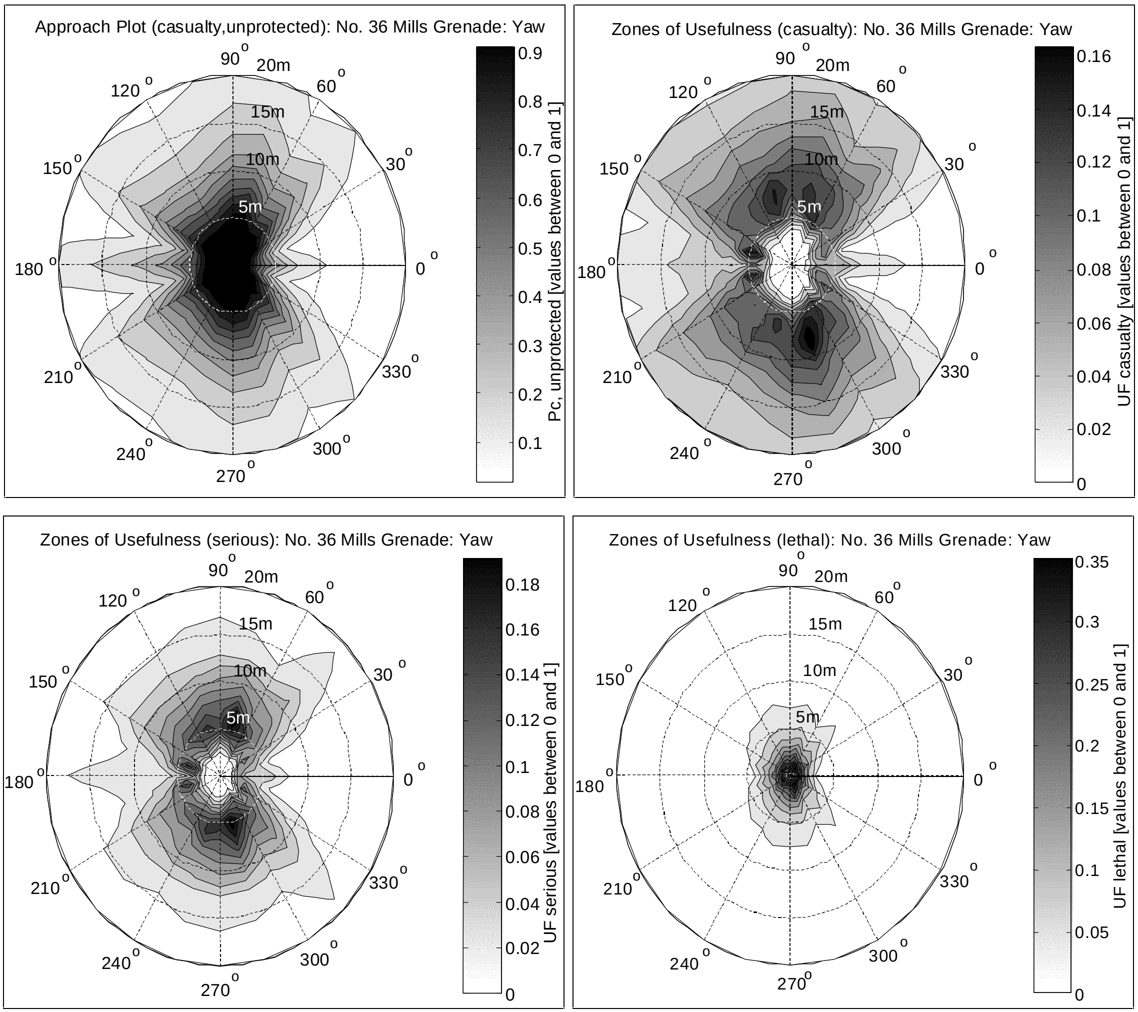


Figures 6.10a b, c & d: Approach plot and zones of usefulness diagrams for an L2A2 grenade

Figures 6.10b & c show that the suit is likely to provide a statistically insignificant ($P < 0.01$) reduction in casualties and serious incapacitation within 3m of the grenade. The EOD operator will probably be seriously injured. However, Figure 6.10d suggests that for this range at 90º and 270º, the suit significantly reduces the probability of dying ($UF_{lethal} = 0.08$). Moreover, wearing the suit is likely to significantly reduce the number of casualties and serious injuries for angles from 30 to 150º and 210 to 330º at ranges between 5 and 20m.

6.4.3 No. 36 Mills grenade

When the position of the fuse is taken into consideration, the safest path towards a No. 36 Mills grenade (Figure 6.12) is at 15º, i.e. just off-line from the fuse (Figure 6.11a).



Figures 6.11 a, b, c & d: Approach plot and zones of usefulness diagrams for a No. 36 Mills grenade

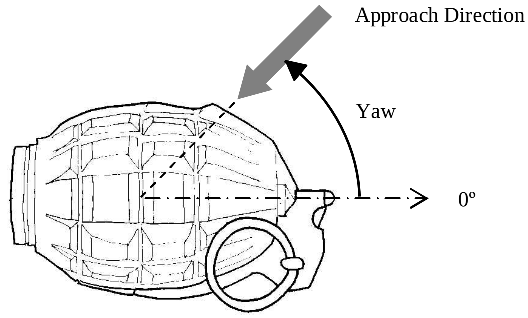


Figure 6.12: No. 36 Mills grenade orientation

Figures 6.11b, c & d show that the Lightweight Combat EOD Suit offers highly significant reductions in deaths and injuries caused when this type of grenade detonates. For people approaching within 2m of this device, $P_{i\ lethal}$ is 0.25 less if the suit is worn. At 285º and 5m, there is a probability of 0.18 that the operator is likely to receive field treatable injuries rather than requiring hospitalisation as a result of wearing the Lightweight Combat EOD Suit.

6.4.4 HB876 area denial weapon

The likely orientation of an HB876 is with the axis of symmetry pointing upwards, due to the self-righting mechanism (Figure 6.13). This means that there is no 'safest' route when approaching an HB876 in this orientation. The relatively small number of symmetrically distributed fragments means that the probability of being hit decreases sharply with increasing range (e.g. from about 0.9 at 1m to 0.3 at 5m) as shown in Figure 6.14a.

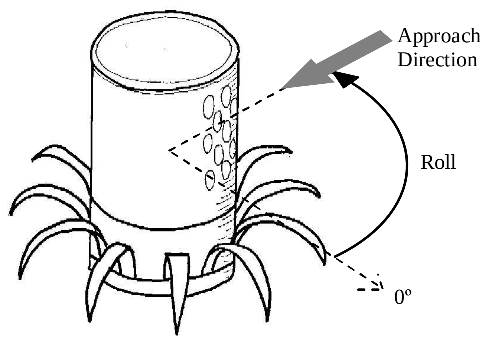
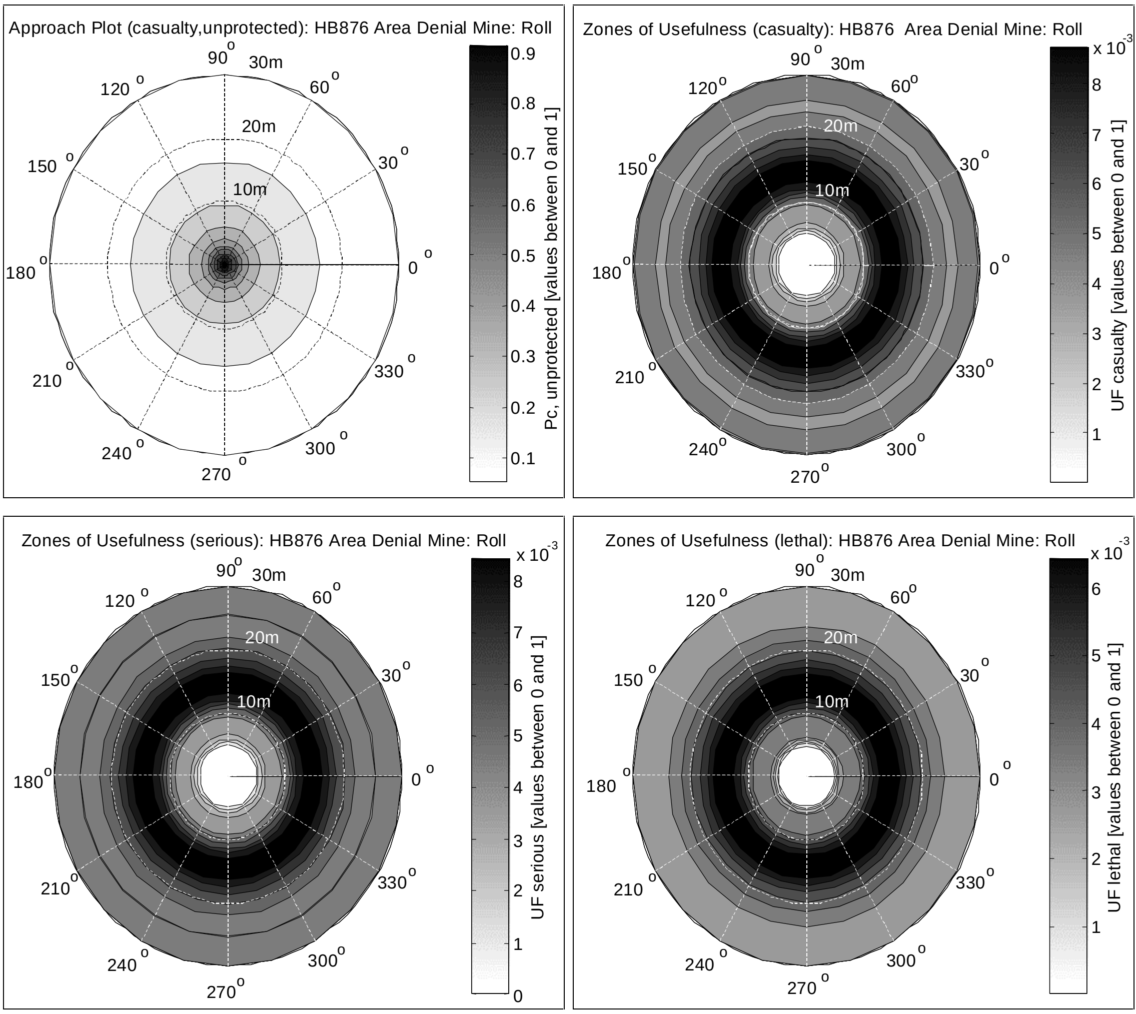


Figure 6.13: HB876 orientation



Figures 6.14a, b, c & d: Approach plot and zones of usefulness diagrams for an HB876 area denial weapon

The zones of usefulness diagrams (Figure 6.14b, c & d) show that, within 30m, the maximum values of *UF* for any incapacitation category are statistically insignificant ($P < 0.01$). There may be little point in wearing a Lightweight Combat EOD Suit to protect against a *single* HB876 mine – as befits a device designed to incapacitate the EOD operator. This is because the fragments are relatively large and penetrative when compared to the BL755.

6.4.5 BL755 sub-munition

The BL755 is a sub-munition that is designed to fall with a vertical axis of symmetry (Figure 6.15). Figure 6.16a illustrates that there is no 'safest' route to approach a BL755 in this orientation. A large number of fragments means that the probability of being hit stays above 0.7 at greater than 10m. However, the relatively small fragment size (compared to the

HB876) and lesser penetrability means that the Lightweight Combat EOD Suit is much more useful against the BL755 than the HB876.

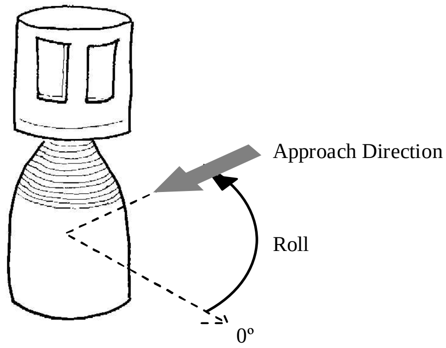
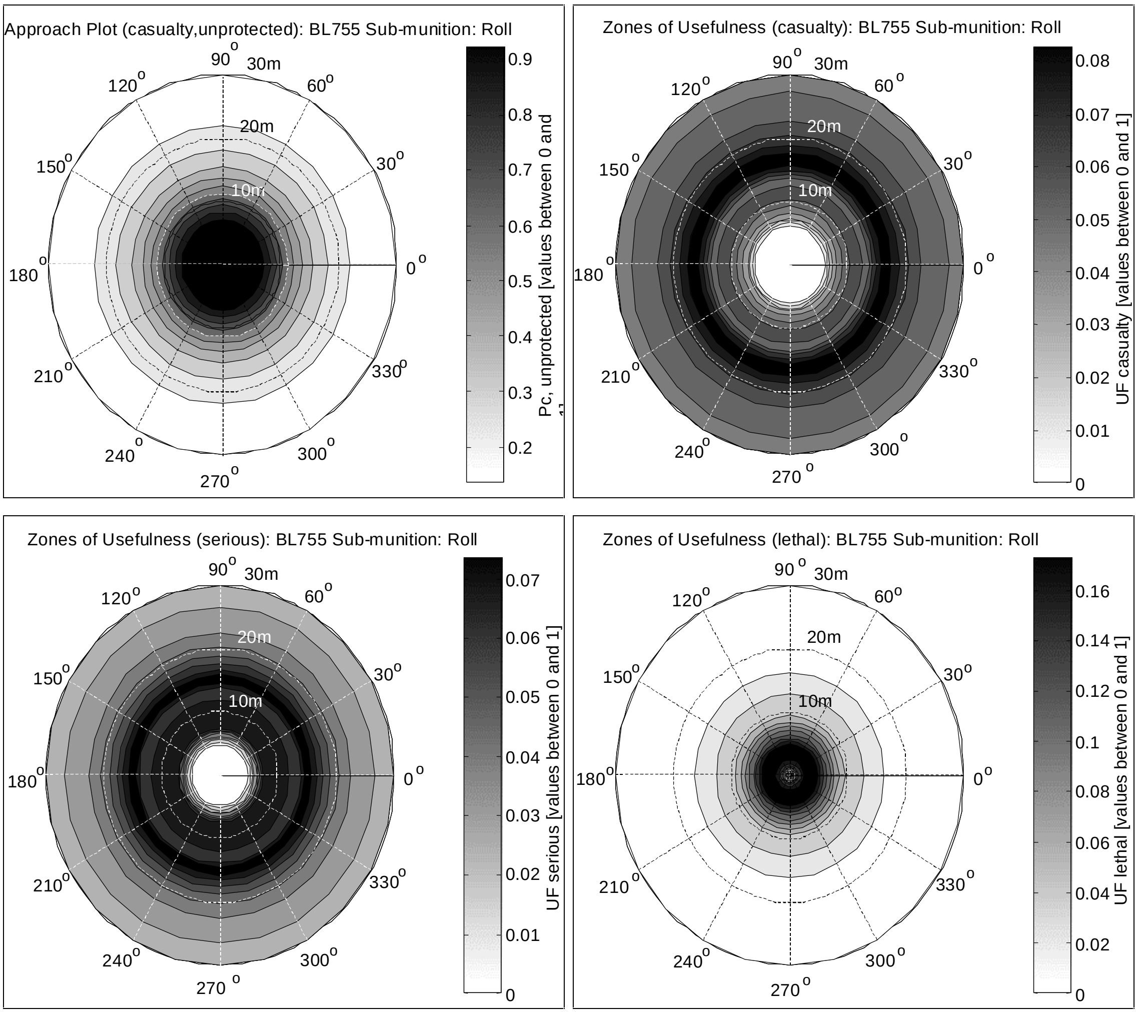


Figure 6.15: BL755 orientation

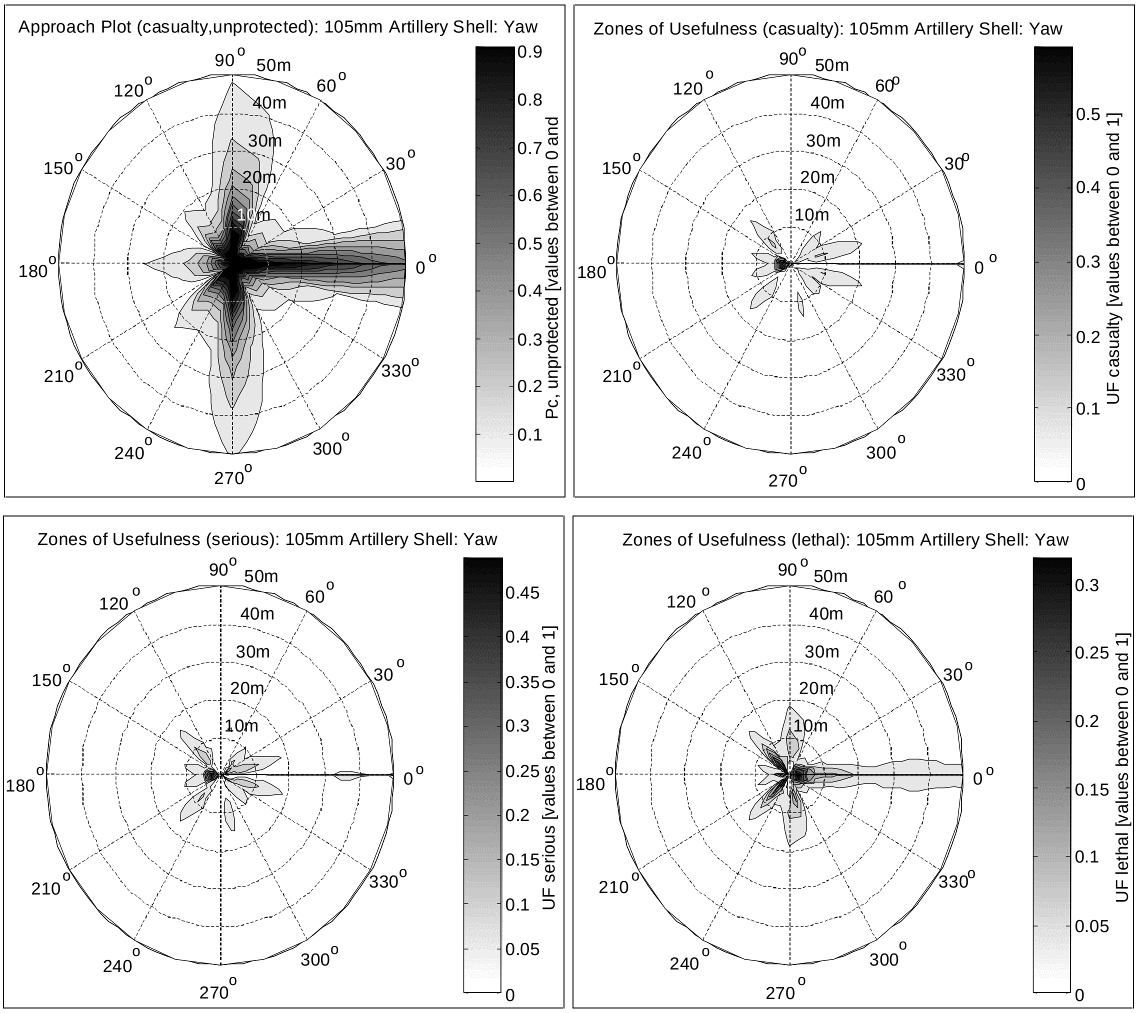


Figures 6.16a, b, c & d: Approach plot and zones of usefulness diagrams for a BL755 sub-munition

At 17m, $UF_{casualty}$ is approximately 0.08: at 10m $UF_{serious}$ is almost 0.07 (Figures 6.16b & c). Between 2m and 5m UF_{lethal} is around 0.16, which is a significant reduction of the probability of dying due to wearing the **Lightweight Combat EOD Suit** (Figure 6.16d).

6.4.6 105mm artillery shell

The approach plot (Figure 6.17a) for the 105mm shell (Figure 6.18) shows the striking difference in $P_{c\ unprotected}$ between yaw angles. Behind the base (0º) $P_{c\ unprotected}$ is about 0.6 at 40m: to the side of the fuse (150º and 210º) it is possible to be at 5m and still have less chance of being hit.



Figures 6.17a, b, c & d: Approach plot and zones of usefulness diagrams for a 105mm shell

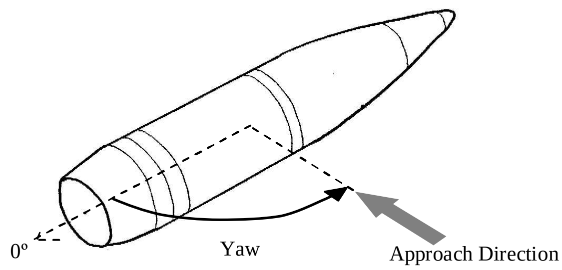


Figure 6.18: 105mm shell orientation

The zones of usefulness diagrams (Figures 6.17b, c & d) show that a useful place to wear the suit around a 105mm shell is when working at the fuse end of the device. However, the blast itself would start to cause lung damage within about a 3m range (Table 6.8).

6.5 DISCUSSION

6.5.1 Protection rather than survivability

One of the key aims of any combat or security force is to minimise the number of friendly casualties. The objective is to minimise P_i and *not* to maximise protection. Some might ask, "Why should armourers focus on protection?" The answer is that measures such as *UF* provide a method of accounting for reductions in P_i in order to assess the relative contribution that personal armour makes. Looking at protection rather than survivability enables the benefits of e.g. stealth to be removed.

6.5.2 Limitations of the assumptions

The assumptions stated in this chapter declare that wearers do not care when, where or how they are injured. This is a simplification, as the author discovered during field trials for the Lightweight Combat EOD Suit. Two, young, male sappers found that a fragment had penetrated the pelvis armour in the genital region. They immediately demanded that protection be increased in that area, while ignoring all other penetrations. This is due to the individual's weighting of the importance of different body parts. Likewise, Stouffer et al (Stouffer et al., 1949) show that soldiers fear certain threats above others. 700 enlisted men from the North African theatre in World War II were surveyed. The majority were most frightened of the German 88mm gun, which they considered to be the most dangerous. Nevertheless, for the purpose of wearer incapacitation, and hence protection, the assumptions hold true.

6.5.3 *UF* as a measure of protection effectiveness

The usefulness factor is a good measure of protection effectiveness because: (a) it is a measure of protection *not* incapacitation; (b) it includes all stages of the incapacitation process and not just that of armour defeat; (c) it excludes reductions incapacitation that are not due to armour; (d) informed users make up their own mind about the value of different levels of incapacitation; (e) it requires approximately the same amount of work to obtain a value of *UF* as other casualty reduction measures.

6.5.4 The five-stage model of protection

A limitation of Equations 6.3 and 6.4 is that they do not account for the synergistic effect of multiple injuries. For example, a person with two bullet wounds is not necessarily twice as likely to die as a person with one bullet wound. Nevertheless, the majority of casualties receive one or two wounds. An American study of 4,600 WIA casualties in Korean War (Beyer, 1962) concluded that "…a large percentage of wounded in action (79 percent) shows only one or two [largely fragmentation] wounds." In recent conflicts in Chechnya 64.8% of Russian gunshot and mine casualties in Chechnya had a single injury (Titius, 2002). Moreover, these are a subset of the total number of combatants, upon which P_i is based.

Models of personal armour subsystems are often based on approximations, judgement calls and assumptions. One example is that the Kokinakis-Sperrazza model of incapacitation due to fragments means that injuries to the arms and legs are assumed to have no lethal effect. However, rupturing the major blood vessels in the thighs could easily kill a soldier in the battlefield. There is certainly a high degree of professional opinion that goes into models such as these. Nevertheless, they should not be discounted from being used to model the personal armour system. The most important point to note is that models need to 'join together' otherwise they are not helpful for design. The constituent stages and their relationships must be continually refined and improved to reflect the growth in knowledge.

The underlying five-stage model remains true despite the limitations of its components. It can be used as a 'simple, back-of-an-envelope' approximation, a detailed computer simulation or an experiment analysis tool, by experienced people who understand the limits and can brainstorm all the potential feedback causes. In fact, the logic behind the five-stage model is robust enough to be used for diverse applications such as vehicle armour or even witness protection schemes.

6.5.5 Approach and zone of usefulness plots

Asymmetry is demonstrated in the approach plots and zones of usefulness diagrams of every device not displayed with a vertical axis of symmetry. This is due to the asymmetry of the crouched person (Figure 6.7). If the real user has their right side forward, then the diagrams would be mirrored in the 0º axis.

The choice of incapacitation categories – i.e. the level of risk – affects strategy and should be part of military doctrine. It should at least be included in a user requirements document for each new armour design.

The sensitivity of the information displayed on the diagrams must be taken into consideration. Contours that are close together show that a small step to the side will result in a large change of probability.

$P_{c\ unprotected}$ does not differentiate between fragment sizes and velocities. If a person chooses to wear armour, then an approach diagram of $P_{c\ armour}$ would be more accurate. However, the first diagram is the best starting point for assessing the safest route.

The diagrams in this chapter are produced on the assumption that an EOD operator knows the orientation and position of the threat. When the orientation is not known, *UF* should be averaged for a given range. When the position is not known, *UF* should be averaged over the area of interest.

The approach plots and zone of usefulness diagrams are based in two dimensions. In the future, a portable computer could be used to assess the situation for three-dimensional orientations. The user would only need to enter the orientations of the threat and operator relative to ground level. Moreover, future battlefield digitisation offers the potential to map multiple threats in relationship to the soldier and his environment to help make other tasks safer.

6.5.6 CASPER

CASPER has a number of limitations in addition to those described in Section 6.5.4. For example, the standard human models are of one size. If one considers that P_{hit} is proportional to the presented target area, then a person's linear dimensions are a major influence on usefulness of armour. Improved casualty reduction analysis models need to include a greater range of anthropometrical data, e.g. relating to lower 95th, 50th and upper 95th percentile male and female armour wearers. Future developments can include a direct link to a digital body scanner† in order to mass customise for armour wearers: as near as practically possible to tailoring.

An additional limitation of CASPER is that blast injury is not included in the current model, which means that the model is not valid very close to a threat. The inner range limit will differ with the size of the explosive charge.

CASPER assumes that the threat detonates. Therefore, it cannot be a complete protection analysis tool unless combined with $P_{occurrence}$. A major potential development is to integrate casualty reduction analysis tools such as CASPER into operational analysis tools such as CAEn, in order to select the best, varying levels of protection throughout a mission

6.5.7 Lightweight Combat EOD Suit

Each approach plot and zone of usefulness diagram in this chapter is based on an EOD operator approaching a *single* threat. When an operator is working around several devices, the probability of being hit may be high but, due to greater ranges, the probability of stopping the fragment may be higher. Thus, the usefulness of the Lightweight Combat EOD Suit around a single HB876 is negligible: whereas, in field of such devices (a likely event, due to the nature of area denial weapons) the suit may prove itself useful. Further research is needed to prove or disprove this hypothesis.

Most of the threats in this chapter are modelled on arena fragmentation data. However, the BL755 is based on limited information from the manufacturer, which should be validated before being accepted.

† http://www.shapeanalysis.com

6.5.8 Minimum ranges at which the Lightweight Combat EOD Suit data are acceptable

Blast is a dominant threat close to an explosive device. However, it diminishes with range more quickly than the threat from fragmentation. This enables the definition of a minimum range, *R*, for which any Lightweight Combat EOD Suit datum in this chapter is acceptable. The question is at what range can one discount blast as an incapacitation mechanism?

The munitions in this chapter are conventional rather than thermobaric (Figure 3.4), at ground level, so it is acceptable to compare their blast characteristics to the parameters for a 1kg TNT hemispherical surface burst (Figure 3.3) (Kingery & Bulmash, 1984). Hopkison-Cranz scaling (Hopkinson, 1915, Cranz, 1926) (Equation 3.1) is used to obtain blast properties for representative masses of TNT. Bowen curves for an unarmoured, 70kg upright man (Bowen et al., 1968) (Figure 3.6) provide the probabilities of incapacitation due to blast lung. Eardrum rupture curves (Richmond & White, 1966) give the likelihood of ear damage.

Table 6.7 presents the minimum ranges, *R*, at which there is less than a 5% chance of eardrum rupture *with* plugs, threshold lung damage and 1% $P_{i\ \mathrm{lethal}}$ due to blast lung for given charge masses of TNT. These criteria are used in this section as a reasonable equivalent to 'casualty', 'serious' and 'lethal' respectively.

TNT mass / kg	$R_{5\%\ eardrum\ rupture}$ / m	$R_{threshold\ lung\ damage}$ / m	$R_{1\%\ \mathrm{lung\ damage}}$ / m
0.1	2.6	0.8	0.6
0.2	3.3	1.1	0.8
0.5	4.8	1.6	1.2
1	6.4	2.1	1.7
2	8.3	3.1	2.1
5	13.5	4.7	2.9

Table 6.7: Minimum ranges for an upright 70kg man from TNT hemispherical surface bursts to avoid 3 levels of blast injury

The content of the munitions is not always TNT so can be more energetic for the same mass; however a proportion of the energy is lost by fragmenting the casing. Thus, it is deemed conservative to compare the blast potential of the munitions with an equivalent charge mass of TNT. The mass of explosive in an L2A2 grenade and 105mm shell is 0.17kg of TNT/RDX and 2.3kg of TNT respectively. The author could not find open literature to suggest the charges in the other munitions, so rough estimates are made from their overall mass and size.

On the basis of the assumptions, information in Table 6.7 and estimations of charge mass, the minimum ranges at which the Lightweight Combat EOD Suit data in this chapter are acceptable are given in Table 6.8.

Threat	$R_{casualty}$ / m	$R_{serious}$ / m	R_{lethal} / m
L2A2 grenade	3	1.0	0.7
No. 36 Mills grenade	3	1.0	0.7
HB876 area denial weapon	4.5	1.5	1.1
BL755 sub-munition	3	1.0	0.7
105mm shell	9	3.5	2.1

Table 6.8: Rough estimates of the minimum ranges at which the Lightweight Combat EOD Suit data in this chapter are acceptable

The thermal threat can be ignored because the Lightweight combat EOD Suit provides sufficient protection according to Calver (1995).

6.6 CONCLUSIONS

1. The protection subsystem can be understood as a five-stage model of occurrence, incidence, resistance, incapacitation and protection with two feedback loops. Any injury mechanism can be applied provided that each stage is understood, even if only as an approximation.

2. Feedback in the protection subsystem must be accounted for by iterating the design process otherwise the assessment of the benefits of armour will be wrong.

3. Current police body armour design is a simplified case of the same system as military armour. If it is no longer reasonable to assume that all threats are targeted and can be stopped then the current go-no go testing will not be enough to understand protection.

4. A suitable and novel measure of protection effectiveness is the usefulness factor, *UF*. This is the difference in probability of incapacitation with and without armour. It is calculated for a single wound as the binomial combination of P_i for each potential event (threat, injury mechanism, body region, etc.), which is integrated over the task duration with respect to time.

5. CASPER has the potential to be an important decision making tool; not just for the armour designer but for the EOD operator as well. Approach plots show the safer routes to a threat, while zones of usefulness highlight areas where the operator is likely to need protection and be protected.

6. There is significant difference in safety when approaching a 105mm shell, between one yaw angle and another. This can be the difference between almost certain life and almost certain death, at the same range. L2A2 and No. 36 Mills grenades positioned on their sides also have important 'safe' routes, which should be known by the EOD operator.

7. The modelling in CASPER suggests that the Lightweight Combat EOD Suit is useful for operators working around L2A2 and No. 36 Mills grenades, and BL755 sub-munitions. These emit large numbers of relatively small fragments, so the likelihood of being hit and protected is high. There is also a narrow zone of usefulness at the fuse end of a 105mm shell lying on its side. However, the Lightweight Combat EOD Suit is not likely to be useful against a lone, upright HB876.

8. CASPER can also be used to calculate the decrease in 'safe' distances due to wearing armour. This helps define the acceptable working area, e.g. the minimum spacing between demining teams.

9. Trials of the Lightweight Combat EOD Suit have been carried out by DLO DC R& PS that help validate the findings in this section.

10. The use of CASPER, which excludes blast, means that the approach plots and zones of usefulness are only acceptable outside of a minimum range, *R*, given in Table 6.8.

6.7 RESEARCH RECOMMENDATIONS

Protection theory can be improved through continuous development of the constituent models, especially those that focus on incapacitation. Topics of particular interest include the synergistic effects of multiple injuries and the doctrinal, qualitative weighting of incapacitation categories. Additionally, further work can extend the knowledge of feedback such as the reduction in speed due to wearing armour.

CASPER can be developed to include all relevant injury mechanisms, e.g. the three stages of blast incapacitation. Moreover, it can be improved by linking it to operational analysis models in order to build up dynamic tasks and to study the effects of multiple threats.

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CHAPTER 7: SECONDARY FRAGMENTATION FROM BURIED AP BLAST MINES: A PROTECTION INPUT (SUB-SUBSYSTEM)

7.1 INTRODUCTION

7.1.1 Aims

To assess the threat of secondary fragmentation from buried AP blast mines by analyzing the results from DLO trial in order to support the development of the Lightweight Combat EOD Suit (Chapter 2.2.3). This may be seen as a specific input to the protection subsystem developed in Chapter 6.

7.1.2 Objectives

- Establish a method of calibrating secondary fragmentation trials data,
- Assess the threat *incidence* in terms of the probability of being hit, P_{hit},
- Evaluate armour *resistance* with the probability of a hit perforating armour, $P_{perforation|hit}$,
- Assess the *incapacitation* of an unarmoured wearer in terms of the probability of an incapacitating hit, $P_{i|hit}$.

7.1.3 Background

Secondary fragments are projectiles that are accelerated by an explosion but are not part of an explosive device. When a buried anti-personnel (AP) blast mine detonates, the surrounding stones become a secondary threat with an ability to wound or kill. It is necessary to understand the potential threat from secondary fragments in order to design the next generation of Explosive Ordnance Disposal (EOD) and countermine suits. This knowledge can also be used to make the jobs such as humanitarian demining safer. It is reported (Trevelyan, 2000) that Afghan deminers work in a squatting rather than prone position – for cultural and ergonomic reasons. This chapter comments on the consequences of this choice for safety and protection.

A conference paper has been presented (Couldrick et al., 2004) that summarises the work carried out in this chapter.

Trials (Figures 7.1 & 7.2) carried out by DCTA (Gotts, 1999) provide an opportunity to assess the threat posed by 2 sizes of secondary fragments during the explosion of buried AP blast mines (50g to 500g) at 2 depths of burial, *DOB*, at a range of approximately 1m and over angles from the vertical (0º) to ground level (approximately 85º) (Table 7.1). Bare plastic explosive (PE4) charges are used to simulate landmines, while removing the effect of casing fragments. The charges are buried in a pit of graded stones that are surrounded by 20-layer strawboard panels at a range of approximately 1m. After detonation, stones above a calibrated velocity limit are caught in the strawboard. This enables their geometrical position and depth into the strawboard to be recorded.

Figure 7.1: DCTA trial showing strawboard and armour targets (Gotts, 1999)

Trial	Mass PE4 /g	DOB /cm	Stones	Trial	Mass PE4 /g	DOB/cm	Stones
1	50	10	small	5	50	5	large
2	100	5	small	6	100	5	large
3	200	5	small	7	200	5	large
4	500	5	small	8	500	5	large

Table 7.1: DCTA trials variables

The front face of each strawboard (British Defence Standards, 1997) panel is divided into nine equal-sized areas. The number of recorded impacts per area is then substituted for the probability of being hit by a stone – *on the condition that it has enough mass and velocity to mark the first layer*. Momentum and kinetic energy densities are used as proxies to discuss the ability of an impact to penetrate armour. A fragment incapacitation model is employed in addition to kinetic energy density, to assess the potential for an impact to wound or kill.

The threat from secondary fragmentation is assessed in terms of the probabilities of being hit, perforating armour and incapacitating an unarmoured person. These may be understood as the *incidence*, *resistance* and *incapacitation (U)* phases of the Five-stage Estimation of Protection described in Chapter 6 (Section 6.2.4).

7.2 THEORY

7.2.1 Probability of being hit, P_{hit}

The number of recorded impacts per unit area is a proxy for the probability of being hit by a stone, P_{hit}. This is the first measure of interest because one of the best defences is to avoid being hit. In this analysis, the front faces (closest to the explosive) of the strawboard panels are divided into 9 equal-sized rectangles as shown in Figure 7.3. The presented area at a given angular position is proportional to the number of rectangles at that angle $n_{rectangles}(\vartheta)$. The number of recorded impacts at that position, $n_{hits}(\vartheta)$, is equivalent to the number of marks on the first layer of each rectangle. It must be remembered that stones with insufficient mass and velocity rebound without making a noticeable mark on the back (away from the charge) of the first layer. Hence, the measures used in this chapter are conditional on stones marking the strawboard. Equation 7.1 states the measure of the conditional probability of being hit that is used.

$$P_{hit|impact\ recorded}(\vartheta) \propto n_{hits}(\vartheta) / n_{rectangles}(\vartheta) \quad (7.1)$$

7.2.2 Probability of a hit perforating armour, $P_{perforation|hit}$

If a projectile hits a target, the next question is “Will armour be defeated?” This is commonly described by the probability of an impact perforating armour, $P_{perforation|hit}$. Common predictors of perforation use the mass, m, and strike velocity, V_s, for specified projectile-armour combinations. However, it is not possible to separate these two variables in the main trials – unlike in the calibration – because multiple stones impact the target simultaneously: An observer cannot identify whether a specific penetration is due to a large, slow fragment or a small, fast one. It *is* possible to use a combination of m and V_s to predict perforation, such as a given projectile’s kinetic energy or momentum.

Investigation (Hetherington, 1996) shows that neither kinetic energy nor momentum transfer to a target during ballistic perforation is independent of V_s. Hence, there is no clear choice of whether to use the kinetic energy or momentum of a projectile to predict target perforation. During discussion (Shu & Hetherington, 1992) that preceded the aforementioned paper, Hetherington states that "Whilst [constant kinetic energy transferred to a perforated target] may be a good approximation for stiff, monolithic plates… I do not believe that it to be so for… a system in which failure is determined by the tensile strain in the backing plate [where] it is the impulse delivered by a round, rather than its kinetic energy, which is critical." In summary, the choice of whether to use kinetic energy, momentum or both depends on the particular projectile and target combination.

The preceding paragraph concerns projectiles of constant dimensions. If the dimensions vary, it is necessary to account for the projectile geometry since pointed projectiles are more penetrative than blunt ones. The common terms are kinetic energy and momentum densities, i.e. the original quantities divided by the contact area, *A*. Evidence is available (McMahon, 1971, Tobin, 1998) of both quantities being applicable for different situations. Tobin uses kinetic energy absorption by a defeated soft ballistic armour to estimate the limit conditions for all projectiles to be stopped (Tobin, 1998). Since this is for a single projectile-target combination, the contact area is constant and is ignored. McMahon predicts the strike velocity of metallic fragments that penetrate and ultimately perforate strawboard, using a model that is based on momentum density as derived in Equation 7.6.

Momentum density, *MD*, and kinetic energy density, *KED*, are given by the formulae

$$MD = mV_s / A \tag{7.2}$$

$$KED = mV_s^2 / (2A) \tag{7.3}$$

A is substituted for a term that includes the density, ρ (= *m* / *volume*), of the projectile. For a spherical projectile, for example, Equations 7.2 and 7.3 become

$$MD = m^{1/3}V_s\rho^{2/3}(16 / (9\pi))^{1/3} \tag{7.4}$$

$$KED = m^{1/3}V_s^2\rho^{2/3}(2 / (9\pi))^{1/3} \tag{7.5}$$

If all projectiles under consideration can be assumed to have a constant density and a constant shape, then

$$MD \propto m^{1/3}V_s \quad (7.6)$$

$$KED \propto m^{1/3}V_s^2 \quad (7.7)$$

Equations 7.6 and 7.7 are used in this chapter to assess the conditional probability of armour being perforated given that it is hit, $P_{perforation|hit|impact\ recorded}$. These are used rather than Equations 7.4 and 7.5 because the effects of stone density and variations in shape are included in the calibration results. Thus, the two models used for the assessment of perforation are

$$P_{perforation|hit|impact\ recorded} \propto m^{1/3}V_s \quad (7.8)$$

$$P_{perforation|hit|impact\ recorded} \propto m^{1/3}V_s^2 \quad (7.9)$$

7.2.3 Probability of a hit incapacitating an unarmoured person, $P_{i|hit}$

No armour is defined in this chapter so the likelihood of incapacitation behind a protective garment cannot be assessed. It *is* possible to consider the probability of incapacitation of an unarmoured person given that they are hit, $P_{i|hit}$. Three measures are used to consider this: *MD* and *KED* as given in Equations 7.6 and 7.7, and the Kokinakis-Sperrazza variable, $mV_s^{3/2}$. Sperrazza and Kokinakis are cited (Sellier & Kneubuehl, 1994) as using a model (Equation 7.10) that is based on momentum density to estimate the threshold velocity, V_{tsh}, for the penetration of human skin. Jauhari and Bandyopadhay are also credited (Sellier & Kneubuehl, 1994) with a model (Equation 7.11) that uses kinetic energy density to make the same estimation. Using either of these forms implies that incapacitation is classified as any penetrating wound. An alternative approach (Kokinakis & Sperrazza, 1965) uses Equation 7.12 to estimate $P_{i|hit}$, where incapacitation is viewed as a reduction in the ability of the person to carry out their job.

$$V_{tsh} = 1.25 / \rho_A + 22 \quad (7.10)$$

$$V_{tsh} = 14.1 / \rho_A^{1/2} \quad (7.11)$$

where V_{tsh} is in ms^{-1}, ρ_A (= m / A) is in gmm^{-2}

$$P_{i|hit} = 1 - e^{-a\left(mV_s^{3/2} - b\right)^n} \quad (7.12)$$

a, *b* and *n* are – classified – parameters that depend on the person's type of activity, body region and time after wounding. Without them, it is only possible to make generalised comments about the effect of secondary fragmentation using this model. However, presenting the trials results for $mV_s^{3/2}$ enables readers with access to the relevant parameters to extend the assessment of incapacitation due to the stones. Therefore, the three models used for assessment of incapacitation are

$$P_{i|hit|impact\ recorded} \propto m^{1/3}V_s \quad (7.13)$$

$$P_{i|hit|impact\ recorded} \propto m^{1/3}V_s^2 \quad (7.14)$$

$$P_{i|hit|impact\ recorded} \propto mV_s^{3/2} \quad (7.15)$$

7.3 METHOD

7.3.1 Trials configuration

An explosive charge of between 50 and 500g is contained within a thin, plastic, open-topped, cylindrical tub (of a type used to hold margarine) that is cut-to-size, in order to simulate the approximate shape of a typical AP blast mine while removing the effects of casing fragments. The depth of burial, *DOB*, (measured from ground level to the top-centre of the charge) is 50 or 100mm in a pit of graded stones that are designated as 'small' or 'large'. Properties of the stones are given in Appendix A.1. Further details of the trials configuration are available in a DCTA report (Gotts, 1999).

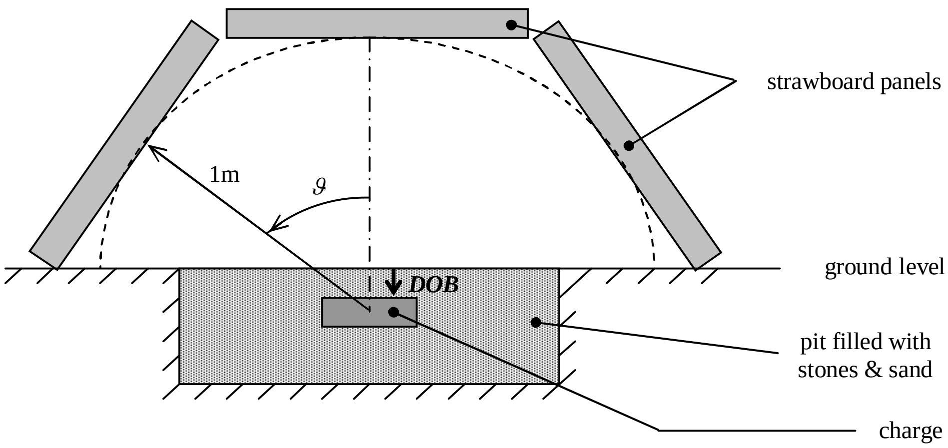


Figure 7.2: Schematic illustration of a trial

Five, 20-layer strawboard panels – designated A to E – are used in each trial. The front faces (layer 1: closest to the explosive) of the panels are divided into 3 by 3, equal rectangles – numbered 1 to 9 – giving an identical area of $0.087m^2$ and a total thickness of 75mm at a range, *r*, of approximately 1m as shown in Figure 7.3. The spherical coordinates of each rectangle centre are given in Appendix A.2. A steel frame is used to maintain these positions during the set-up of each trial.

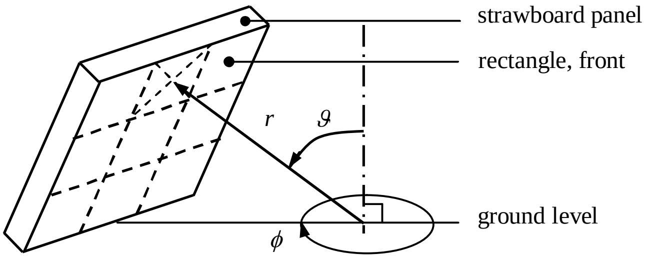


Figure 7.3 Spherical coordinates of the rectangle centres

7.3.2 Impact measurement

After detonation of the charge, stones with sufficient mass and velocity are caught in the strawboard panels. The number of marks on the rear face (furthest from the explosive) of each rectangle on each layer is counted. These are perforation, penetration or witness marks (Figure 7.4). A perforation is a hole where a stone has passed through to affect the next layer. The ultimate trace of a stone is a witness mark or penetration, which are identified when a dent on the rear face of a layer is felt by the observer. The subjectivity that this introduces is considered in the Sources of Error and Research Recommendations sections of this chapter.

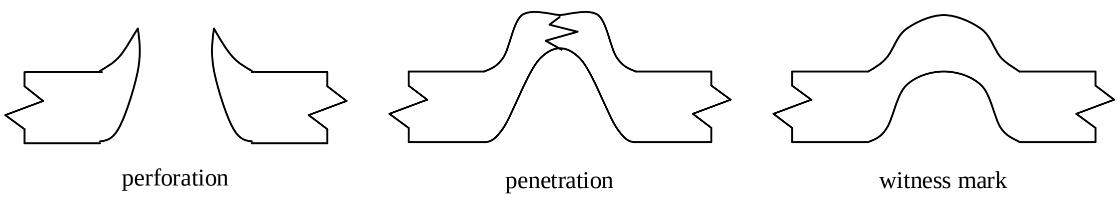


Figure 7.4: Different types of impact marks

7.3.3 Data transformation

n_{hits} (number of marks on layer 1 per rectangle) is a direct measurement in the trials. Hence, Equation 7.1 is plotted with no need for confidence limits. However, the three different models used for perforation of armour and incapacitation of an unarmoured person ($m^{1/3}V_s$, $m^{1/3}V_s^2$ and $mV_s^{3/2}$) must be calibrated against the maximum depth of witness mark or penetration, d. This is described in the following section.

Raw trials data (Appendix A.6) are transformed in Matlab®† using the file main.m (Appendix A.7) and the calibration results from cal.m (Appendix A.4) into a form that is plotted in Appendix A.8.

7.4 CALIBRATION

7.4.1 Calibration introduction

Stones from the same batches as those used in the DCTA trials are shot into 20-layer panels of standard strawboard in order to calibrate the trials data. Identical strawboard panels have been calibrated (McMahon, 1971) for metallic fragments using the depth of penetration and fragment mass, m, to calculate the strike velocity, V_s. This can be rearranged to use the depth of penetration as the sole independent variable using the form in Equation 7.6. However, the stones break up during the impact and it is no longer relevant to measure their depth of penetration. An alternative is to measure the maximum depth over which the strawboard is permanently deformed, d. The ultimate trace of an impact is shown on the rear surface of one of the layers as either: (a) a penetration where the strawboard is split or (b) a witness mark where strawboard bulges but is not split (Figure 7.4). Three empirical models are required for the combinations of V_s, and m as functions of d. These enable calibration of the trials data for proxies of the momentum and kinetic energy densities, and the Kokinakis-Sperrazza variable.

† MathWorks, USA. http://www.mathworks.com

7.4.2 Calibration method

A sample of the stones used in the trials are shot from a shotgun, one-at-a-time, into twenty-layer panels of standard strawboard. Each stone's mass and strike velocity are recorded, as well as the number of layers that are permanently deformed. More details of the calibration procedure and apparatus are as follows.

1. Load a CCI 209 primer into a 12-gauge, 70mm shotgun cartridge (Figure 7.5).

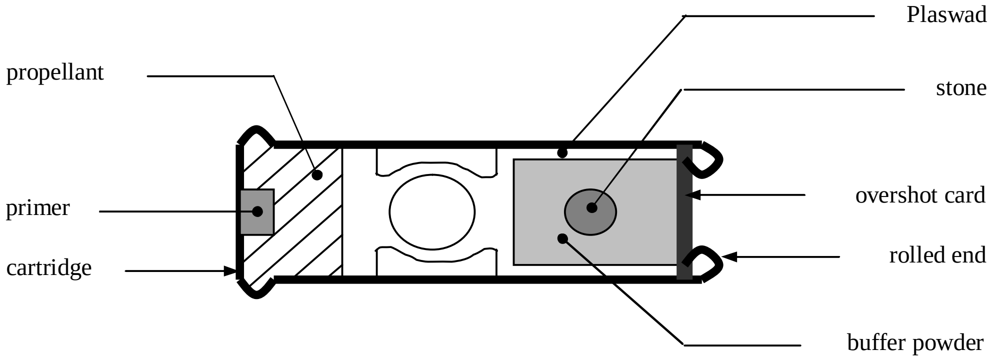


Figure 7.5: Cross-section of a loaded 12-gauge shotgun cartridge

2. Load the propellant into the cartridge. In the experiment, between 1.0g of Hercules Green Dot (medium vivacity shotgun) propellant and 3.3g of Bullseye pistol propellant is used.
3. Make four, equally-spaced slits in an S28 Plaswad (plastic wadding cup), from the rim to the base of the cup. This helps slow down the Plaswad as it leaves the barrel. Put the Plaswad into the cartridge.
4. Half fill the Plaswad cup with buffer powder. The polypropylene buffer powder prevents the stone from breaking up as the shot is fired.
5. Measure the mass, m of the stone and place this in the Plaswad.
6. Top up the Plaswad with buffer powder.
7. Close the cartridge with an overshot card and, using a loading tool, roll the end of the cartridge over.
8. Mark the shot number on the cartridge.
9. Steps 1 to 8 are repeated to load the required number of cartridges (63 in this experiment).
10. Set up the rig, as shown in Figure 7.6.
11. Fire the shot and read the strike velocity, V_s from the timer.

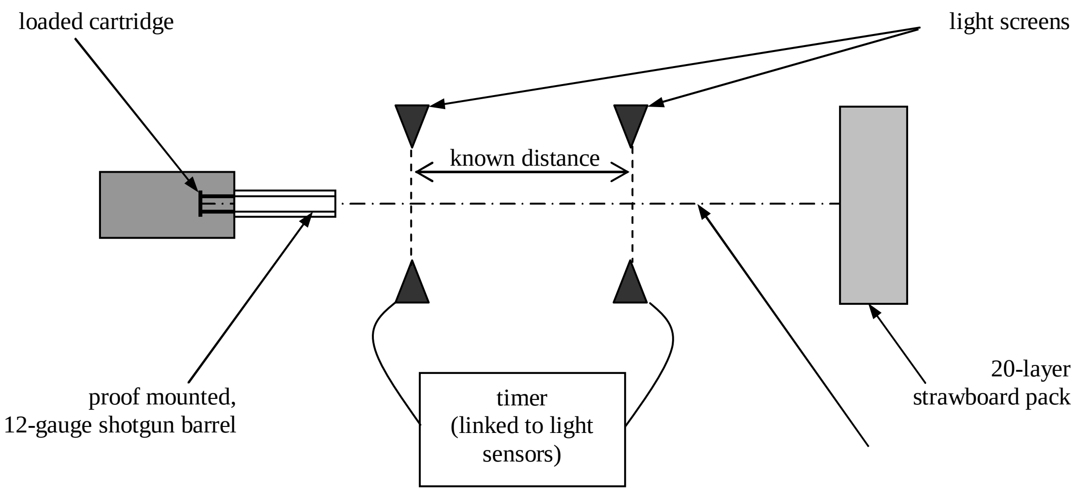


Figure 7.6: Secondary fragment calibration rig

12. Mark the impact with the shot number.
13. Repeat steps 10 to 12 for all the shots, replacing the target after every ten shots to prevent impacts from being too close to each other.
14. For each shot, count the number of layers where a dent can be felt on the back of the strawboard. Convert the depth, *d* from layers to mm, using the fact that 20 layers equal 75mm.

Regression analysis using the program cal.m (Appendix A.4) fits the models to the calibration raw data within 95% tolerance limits. The equations are and their associated statistics are used to discuss the validity of the calibration results. Graphs of the results within tolerance limits are presented in Appendix A.5 and are used to predict single values in the main trials.

7.4.3 Calibration results

The raw data is presented in Appendix A.5. Regression analysis of the sixty-three hits gives the following models using V_s (in ms^{-1}), *m* (in g) and *d* (in mm) corresponding to Equations 7.8, 7.9, 7.13, 7.14 and 7.15. Model A is linear, while models B and C are second-order polynomials for the natural logarithm of the dependent variable, in order to obtain acceptable fits as identified by the *t*-statistics and R^2 values.

Model A: Proxy for momentum density

$$m^{1/3}V_s = \underset{(4.99)}{151.0} + \underset{(14.64)}{21.35d} \tag{7.16}$$

$n = 63$ $R^2 = 0.778$ $s = 113.5$

Model B: Proxy for kinetic energy density

$$\log_e(m^{1/3}V_s^2) = \underset{(48.51)}{10.58} + \underset{(5.80)}{0.1408d} - \underset{(-3.19)}{0.001871d^2} \tag{7.17}$$

$n = 63$ $R^2 = 0.676$ $s = 0.4782$

Model C: Kokinakis-Sperrazza variable

$$\log_e(mV_s^{3/2}) = \underset{(33.83)}{6.697} + \underset{(9.29)}{0.2049d} - \underset{(-5.02)}{0.002673d^2} \tag{7.18}$$

$n = 63$ $R^2 = 0.848$ $s = 0.4338$

Where t-statistics for each coefficient are given in parentheses; n = number of observations; R^2 = coefficient of determination; s = standard error of the regression

7.4.4 Calibration discussion

Models A, B and C explain 77.8, 67.6 and 84.8% respectively of the variation. Therefore, factors other than the stone's mass and maximum depth of penetration or witness mark have a significant influence on the calculation of V_s. This is not surprising given, for example, the widely varying shapes of the stones. A 'pointed' stone will penetrate more layers of strawboard than a 'flat' stone of the same mass. Moreover, variations in the stones' densities increase the deviations from the models. A further explanation of n, t-statistics, R^2 and s is found in statistics textbooks (Fleming & Nellis, 1997).

Another important source of error is the human judgement called on to identify permanent deformations of the strawboard due to stone impacts. To minimise the effects of human error, the same observer recorded all the perforation, penetration and witness mark depths.

If other factors, such as shape, are taken into consideration the models will be more accurate (smaller standard errors). However, the purpose of this experiment is to calibrate the strawboard for the three dependent variables when the shape is not known and the density is assumed to be constant. Therefore, the models are deemed adequate for their intended use.

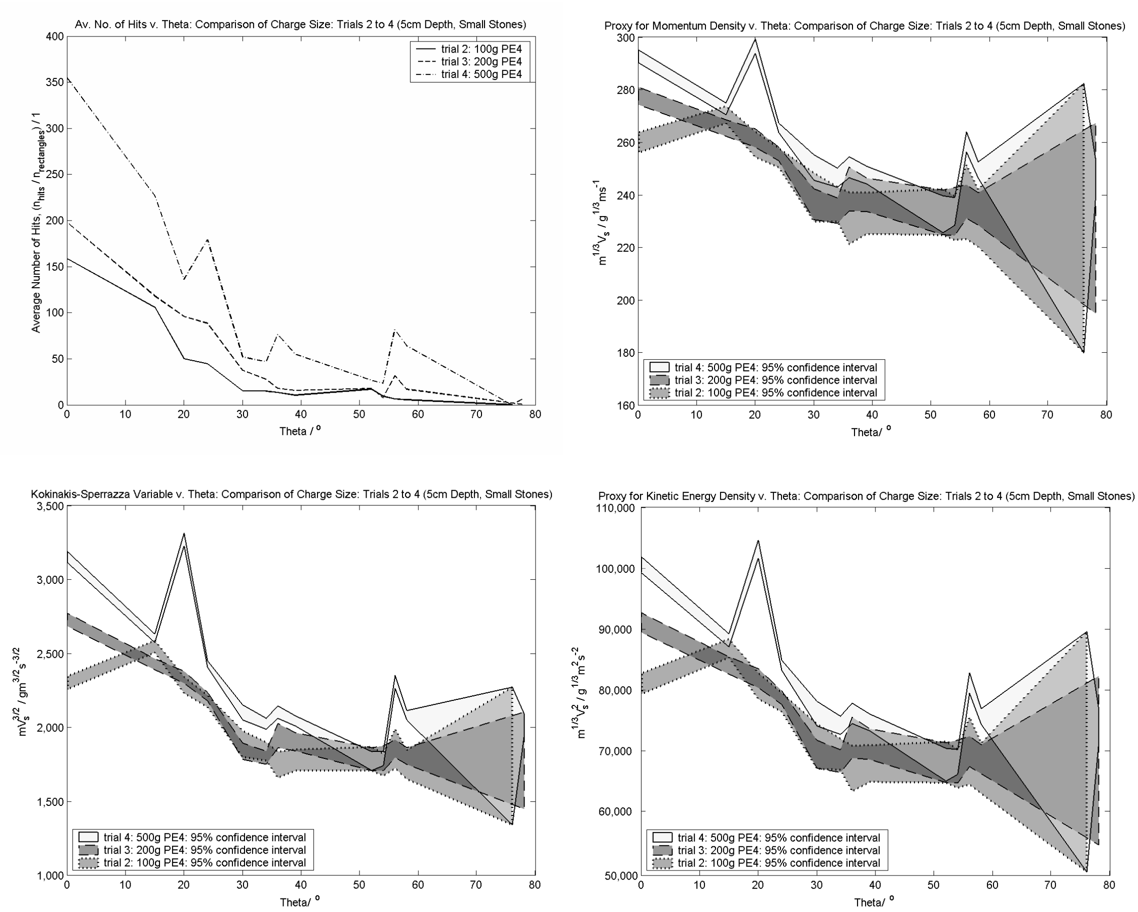
7.4.5 Calibration conclusions

It is highly likely that the true strike properties of 95% of new stone impacts into twenty-layer strawboard panels will be within the 95% tolerance limits of models A, B & C (Appendix A.5).

7.5 RESULTS

The raw trials data are given in Appendix A.6. Plots of Equation 6.1 and models A,B and C are presented for each trial in Appendix A.8. The mean value plus, where applicable, 95% confidence limits are superimposed in the following graphs (Figures 7.7a to 7.12d) to compare the effects of varying the charge size, stone size and the combination of charge depth and stone size.

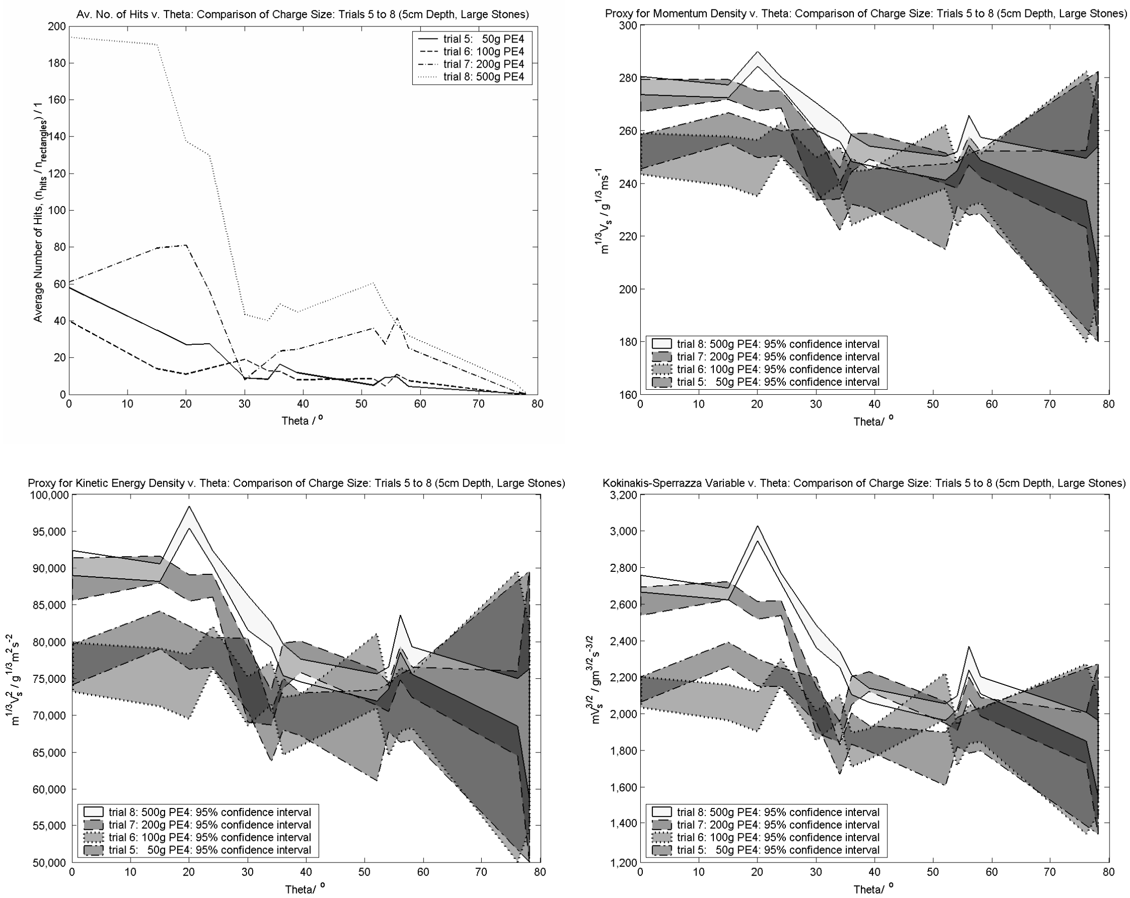
7.5.1 Comparison of charge size: trials 2 to 4



Figures 7.7a, b, c & d: Comparison of charge size: trials 2 to 4 (5cm depth, small stones)
(a) average number of hits versus theta, (b) proxy for momentum density versus theta,
(c) proxy for kinetic energy density versus theta, (d) Kokinakis-Sperrazza variable versus theta

NB All dependent variable values are conditional on impacts marking strawboard.

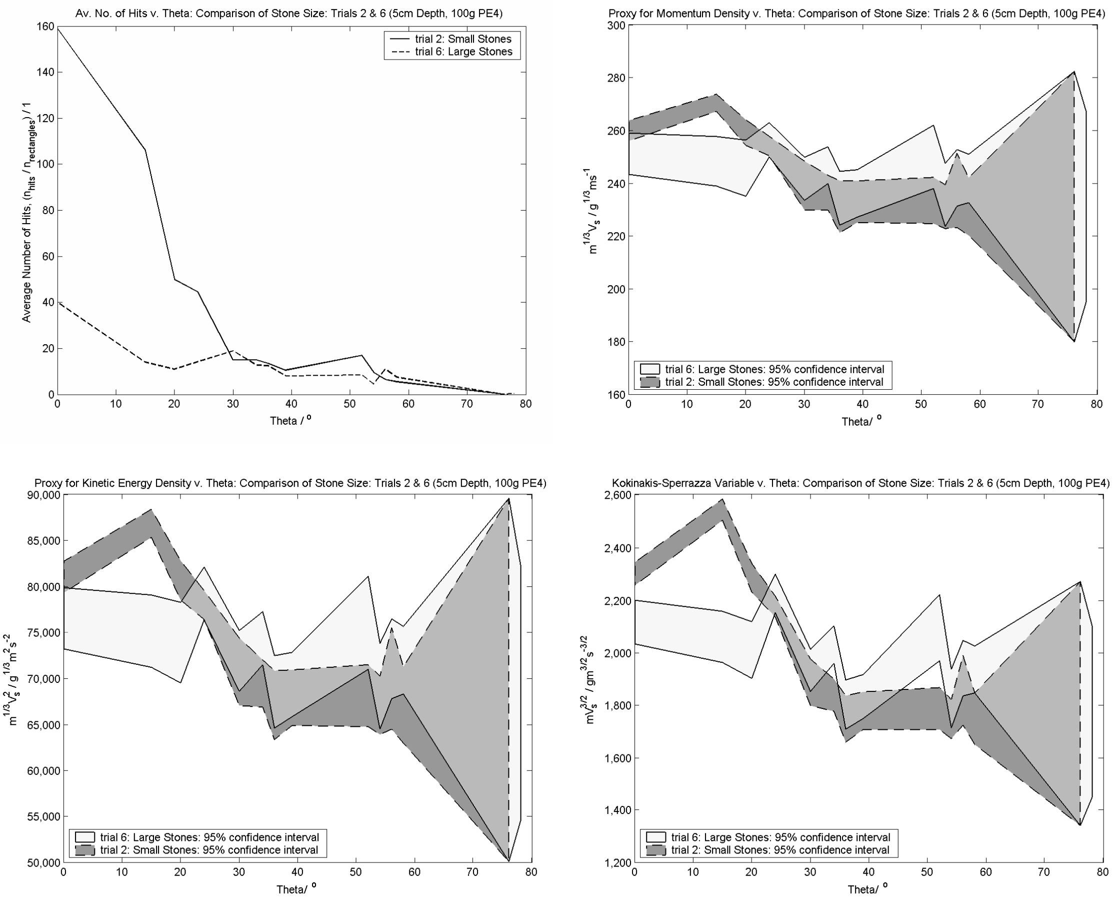
7.5.2 Comparison of charge size: trials 5 to 8



Figures 7.8a, b, c & d: Comparison of charge size: trials 5 to 8 (5cm depth, large stones)
(a) average number of hits versus theta, (b) proxy for momentum density versus theta,
(c) proxy for kinetic energy density versus theta, (d) Kokinakis-Sperrazza variable versus theta

NB All dependent variable values are conditional on impacts marking strawboard.

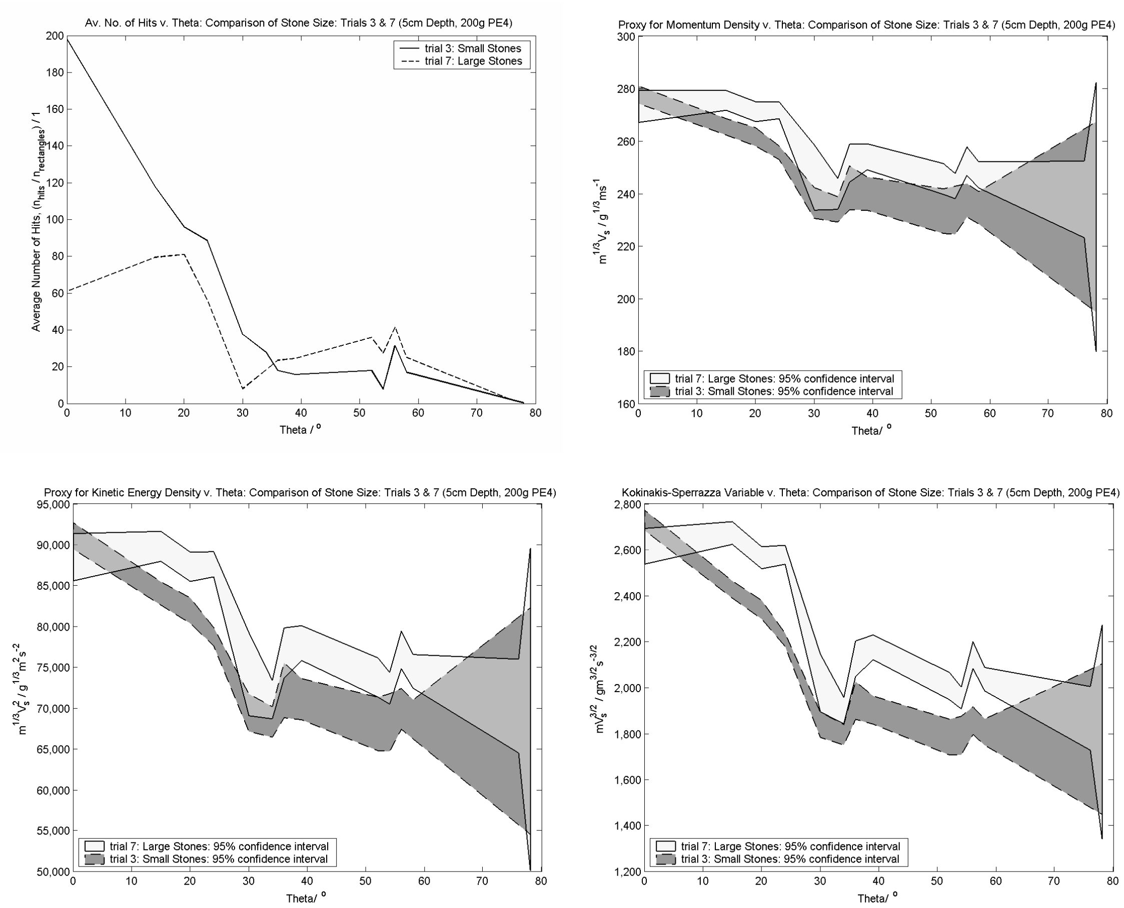
7.5.3 Comparison of stone size: trials 2 & 6



Figures 7.9a, b, c & d: Comparison of stone size: trials 2 & 6 (5cm depth, 100g PE4)
(a) average number of hits versus theta, (b) proxy for momentum density versus theta,
(c) proxy for kinetic energy density versus theta, (d) Kokinakis-Sperrazza variable versus theta

NB All dependent variable values are conditional on impacts marking strawboard.

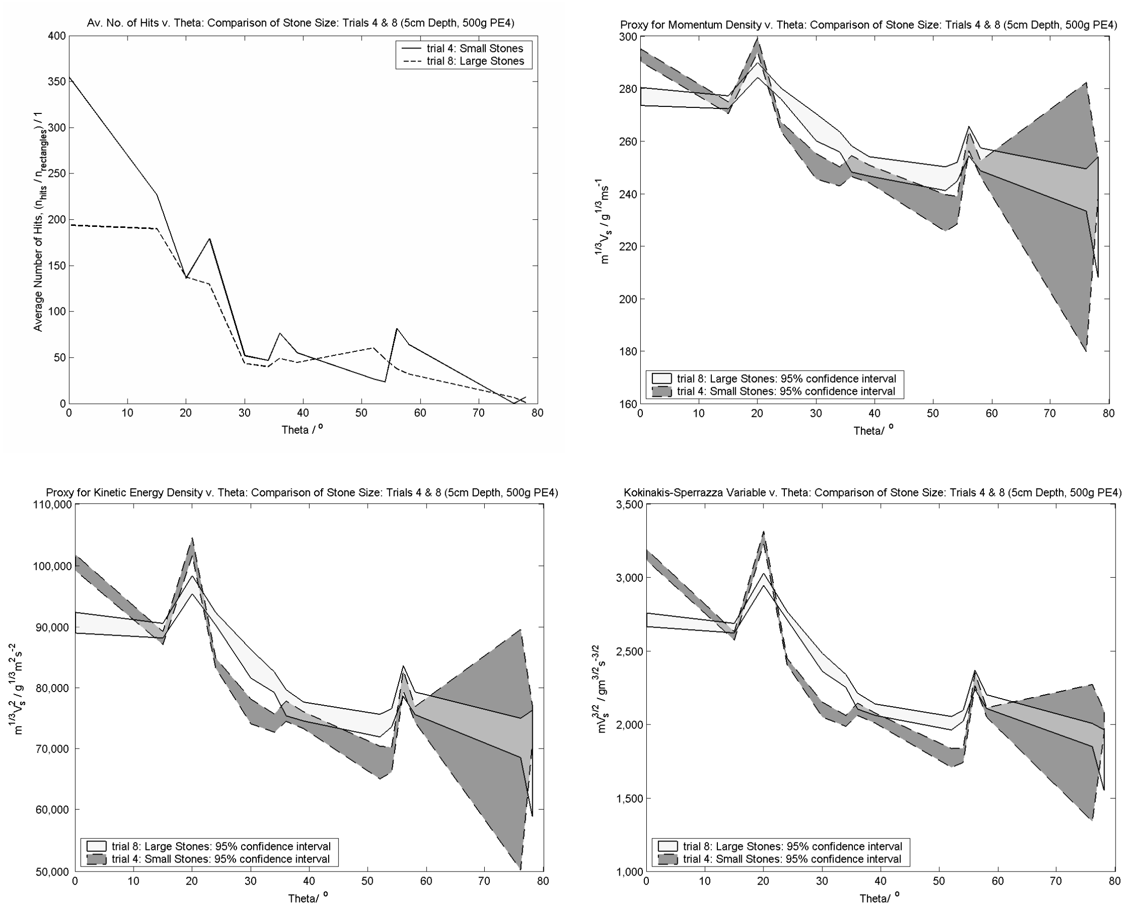
7.5.4 Comparison of stone size: trials 3 & 7



Figures 7.10a, b, c & d: Comparison of stone size: trials 3 & 7 (5cm depth, 200g PE4)
(a) average number of hits versus theta, (b) proxy for momentum density versus theta,
(c) proxy for kinetic energy density versus theta, (d) Kokinakis-Sperrazza variable versus theta

NB All dependent variable values are conditional on impacts marking strawboard.

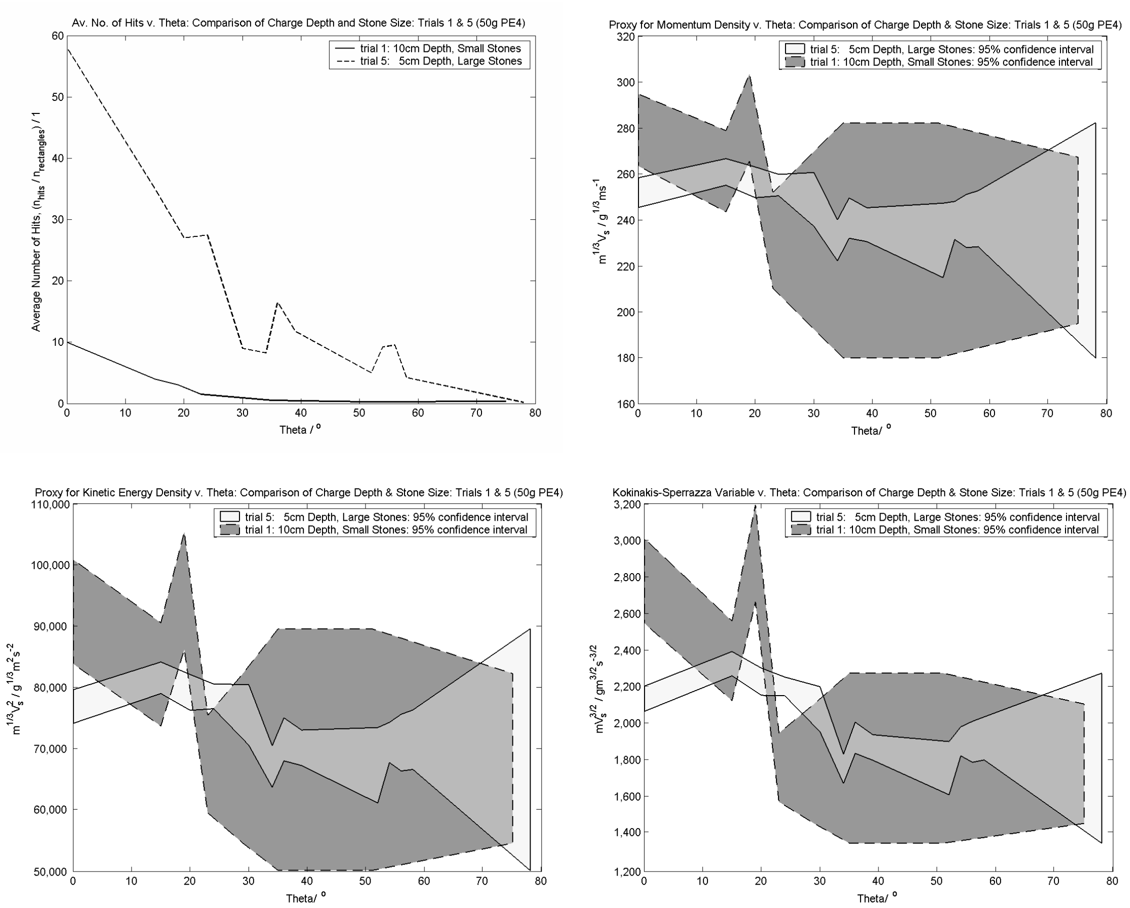
7.5.5 Comparison of stone size: trials 4 & 8



Figures 7.11a, b, c & d: Comparison of stone size: trials 4 & 8 (5cm depth, 500g PE4) (a) average number of hits versus theta, (b) proxy for momentum density versus theta, (c) proxy for kinetic energy density versus theta, (d) Kokinakis-Sperrazza variable versus theta

NB All dependent variable values are conditional on impacts marking strawboard.

7.5.6 Comparison of charge depth and stone size: trials 1 & 5



Figures 7.12a, b, c & d: Comparison of charge depth and stone size: trials 1 & 5 (50g PE4)
(a) average number of hits versus theta, (b) proxy for momentum density versus theta,
(c) proxy for kinetic energy density versus theta, (d) Kokinakis-Sperrazza variable versus theta

NB All dependent variable values are conditional on impacts marking strawboard.

7.6 DISCUSSION

7.6.1 Probability of being hit

The mean $P_{hit|impact\ recorded}$ (ϑ) decreases towards zero as ϑ increases to ground level. Two distinct regions are identified: 0° to X ($X \approx 30°$ for trials 2 to 8 or $\approx 23°$ for trial 1) has a greater rate of decrease than X to 80°, which has a lesser rate of decrease. There is approximately a 50 to 85% reduction in the conditional probability of being hit at $X < \vartheta < 80°$ when compared to 0°. It is proposed that the trend for decreasing mean $P_{hit|impact\ recorded}$ (ϑ) is due partly to energy being channelled upwards in a blast cone and partly due to the increasing thickness of the layer of stones as ϑ increases: Less of the explosive's energy is transferred to each stone on average as ϑ increases. It is further proposed that the two regions arise due the crater shape. Stones that impact within a cone enclosed by the crater radius will have been accelerated in, more or less, a straight line from the centre of detonation. Those that impact outside the crater radius will have undergone relatively greater frictional energy losses due along a non-linear path, in addition to receiving a reduced proportion of blast energy.

Increasing the charge size scales up the mean $P_{hit|impact\ recorded}$ (ϑ), e.g. increases it by a percentage, as there is more energy to be transferred to all secondary fragments. The distribution remains the same for the reasons outlined above.

Increasing the stone mass for a constant density reduces the mean $P_{hit|impact\ recorded}$ (ϑ) for the region 0° to X as fewer stones are involved in an explosion. However, in the region X to 80°, the conditional likelihood of being hit is approximately the same for small and large stones. It is proposed that this is due to larger stones losing less energy than small ones, e.g. owing to a lower surface area per unit volume.

It is not possible to look at the effects of altering the charge depth independently of other variables with the available trials results. This is because the trials were changed after it was found that 50g of PE4 at a 10cm depth of burial produced few impacts. Nevertheless, comparing trials 1 & 5 (Figure 7.12a) with trials 2 & 6 (Figure 7.9a) hints that, with this particular set up, increasing the charge depth reduces the mean $P_{hit|impact\ recorded}$ (ϑ) for all values of ϑ. It is proposed that this is due to a greater thickness of stones in all directions: The same explosive energy is spread to more materiel. However, it is acknowledged that alternative trials conditions may demonstrate an increased mean $P_{hit|impact\ recorded}$ (ϑ) at 0° with increasing charge depth as the blast energy is more narrowly channelled upwards.

7.6.2 Probability of a hit perforating armour

Despite peaks that are discussed in Section 7.6.5, the general trend for the mean conditional *MD* and *KED* values of the secondary fragments used in this chapter is to decrease from 0° to approximately 50°. Stones are not only less likely to hit targets at 50° compared to 0° but it is also likely that they are less able to perforate armour. This supports the theory that less of the explosive's energy is transferred to each stone on average as ϑ increases. It is not possible to state what happens between this region and ground level because the variance of the estimated *MD* and *KED* values to achieve 95% confidence is too large.

There is evidence that increasing the charge size increases the mean $P_{perforation|hit|impact\ recorded}$. For example, in Figures 7.7b & c the estimates of mean *MD* and *KED* for 500g PE4 remain greater than those for 100 and 200g. Importantly, there is no evidence, within 95% confidence limits, that either value decreases with increasing charge size at any value of ϑ.

There is no clear evidence that enables the observer to state that increasing the stone mass for a constant density either increases or decreases the mean $P_{perforation|hit|impact\ recorded}$ for all charge sizes under consideration. The results shown in Figures 7.9b & c, 7.10b & c and 7.11b and c show evidence of both increased and decreased mean values of *MD* and *KED* as a result of increased stone mass.

The large variance of the estimates of mean *MD* and *KED* make it difficult to draw strong conclusions about varying the charge depth in addition to the stone size. It is possible to say that, within 95% confidence limits, the mean $P_{perforation|hit|impact\ recorded}$ is less for trial 5 (5cm depth, large stones) than for trial 1 (10cm depth, small stones) at 0° as shown in Figures 7.12b & c. Moreover, the opposite is true at approximately 23° as given in Figure 7.12c. This is very limited evidence and further work should be carried out to clarify the effects of varying the charge depth. Nevertheless, it does hint that the channelling effect of a increasing charge depth can make stones directly above more able to perforate armour whilst making those to the side less dangerous.

It is possible to compare the perforation potential of a spherical secondary fragment (*s.f.*) with the properties of a spherical primary fragment (*p.f.*) to achieve the same $P_{perforation|hit}$ by using Equations 7.4 and 7.5 to transform Equations 7.19 & 7.20 into Equations 7.21 and 7.22.

$$MD_{p.f.} = MD_{s.f.} \tag{7.19}$$

$$KED_{p.f.} = KED_{s.f.} \tag{7.20}$$

$$m_{p.f.}{}^{1/3}V_{s\,p.f.}\,\rho_{p.f.}{}^{2/3} = m_{s.f.}{}^{1/3}V_{s\,s.f.}\,\rho_{s.f.}{}^{2/3} \tag{7.21}$$

$$m_{p.f.}{}^{1/3}V_{s\,p.f.}{}^{2}\rho_{p.f.}{}^{2/3} = m_{s.f.}{}^{1/3}V_{s\,s.f.}{}^{2}\rho_{s.f.}{}^{2/3} \tag{7.22}$$

The maximum estimated mean conditional values of $m^{1/3}V_s$ and $m^{1/3}V_s^2$ in any of the secondary fragment trials are approximately 300$g^{1/3}ms^{-1}$ and 100,000$g^{1/3}m^2s^{-2}$ respectively. ρ of the stone material is a worst case at around 2000kgm^{-3} (see Appendix A.1). Typical primary fragments are 1.1g steel spheres (ρ = 7800 kgm^{-3}). Hence, V_s for 1.1g steel spheres that give the same $P_{perforation|hit}$ as the worst case average conditional of secondary fragments in the trials is 117ms^{-1} if *MD* is an appropriate model or 198ms^{-1} if *KED* is used. These values are well below the limits of modern ballistic armours and the velocities expected from 1.1g fragments in AP fragmentation mines.

7.6.3 Probability of a hit incapacitating an unarmoured person

The mean $P_{i|hit|impact\ recorded}$ based on the perforation of skin follows the same trends as those described in Section 7.6.2 because either *MD* or *KED* is used. Moreover, the values of the Kokinakis-Sperrazza variable also follow similar trends. One notable exception is that there is limited evidence in Figure 7.7d (trial 2 at $\vartheta \approx 16°$) and Figure 7.8d (trial 5 at $8° \leq \vartheta \leq 19°$) that contradicts the prediction that the mean $P_{i|hit|impact\ recorded}$ increases with charge size. This is an issue for further investigation.

A similar approach to that outlined above is used for the mean conditional $mV_s^{3/2}$, which has a maximum value in any of the trials of approximately 3000$gm^{3/2}s^{-3/2}$. Using Equation 7.12 for a primary and a secondary fragment gives the following equation since *a*, *b* and *n* remain constant for the two cases.

$$m_{p.f.}V_{s\,p.f.}{}^{3/2} = m_{s.f.}V_{s\,s.f.}{}^{3/2} \tag{7.23}$$

Provided that Kokinakis-Sperrazza is an appropriately shaped model, a 1.1g steel spherical fragment with a V_s of 195ms^{-1} gives the same $P_{i|hit}$ as the worst case average conditional secondary fragment.

Using Equations 7.10 and 7.11 for a 1.1g steel sphere (A = 32.76mm^2) gives V_{tsh} values of 59ms^{-1} and 77ms^{-1} respectively. The lowest mean conditional proxies for *MD*, *KED* and the Kokinakis-Sperrazza variable for any trial are approximately 235g$^{1/3}$ms^{-1}, 67,000g$^{1/3}$m^{2}s^{-2} and 1,700gm$^{2/3}$s$^{-2/3}$. These are equivalent to 1.1g steel fragments with strike velocities of 92, 162 and 134ms^{-1} respectively. Therefore, it is likely that a naked person will be incapacitated by the secondary fragments alone at any angle of ϑ.

7.6.4 General observations

Nearly all the stones break up into dust. The associated loss of energy means that this particular type of stone may be easier to stop than fragments of tougher materials. Moreover, the stones often have a rounded shape. Fragments with sharp points are likely to be more penetrative.

The variance of estimates is dependent on the number of impacts. Hence, the variance increases as ϑ increases until it is impossible to assess the trials variables close to ground level.

The estimates for P_{hit}, $P_{perforation|hit}$ and $P_{i|hit}$ in this chapter are mean conditional values. The condition that impacts must have sufficient m and V_s to mark the strawboard is conservative and results in the estimates being lower than the true mean values. However, using the mean implies that 50% of impacts will have greater abilities to defeat armour and incapacitate an unarmoured person. Reviewing the trials raw data (Appendix A.6) gives the following maximum values of d for the minimum values of ϑ in any of the trials (Table 7.2). The range of strike velocities – i.e. between the 95% tolerance limits in models A, B and C – for a 1.1g steel spherical fragment are found using aforementioned procedure and the densities of stone and steel as 2000 and 7800kgm^{-3} respectively.

ϑ	*d* / layers	*d* / mm	Model A		Model B		Model C	
			lower V_s / ms^{-1}	upper V_s / ms^{-1}	lower V_s / ms^{-1}	upper V_s / ms^{-1}	lower V_s / ms^{-1}	upper V_s / ms^{-1}
78	2	7.50	31	212	123	326	114	371
76	3	11.25	63	243	150	396	168	543
58	4	15.00	95	274	178	470	236	761
24	10	37.50	280	464	280	779	601	2070

Table 7.2: The most dangerous impacts in any trial and the equivalent properties of 1.1g spherical steel fragments

The strike velocities in Table 7.2 are the upper and lower limits for the most dangerous secondary fragments in any of the trials. These confirm that a naked person is likely to be incapacitated (model A, B and C) by secondary fragmentation at any angle of ϑ. They also confirm that secondary fragments are less able to defeat armour than primary fragments (models A and B).

The findings in this chapter are corroborated by the effects on armour items (Figure 7.1) in DCTA's trials report (Gotts, 1999).

7.6.5 Sources of error

Any stone that rebounds without leaving a recorded mark is not included in the calculation of the dependent variables. This means that the true mean P_{hit}, $P_{perforation|hit}$ and $P_{i|hit}$ values are lower than suggested by the results.

As the number of recorded impacts increases (e.g. with larger charge sizes), so does the frequency of multiple strikes in the same spot. This means that all the impacts in the front face cannot be counted. It also means that the true mean P_{hit}, $P_{perforation|hit}$ and $P_{i|hit}$ values are lower than suggested by the results.

The strawboard panels are flat but the blast wave accelerates the stones from, approximately, a point source. This means that the incidence angle, β, (Figure 7.13) will vary depending on the geometric position of the target as given in Appendix A.2 and plotted in Figure 7.14. Therefore, stones hitting the rectangles at the corners of the strawboard panels (approximately 29º < ϑ < 39º) are more likely to rebound than those hitting the strawboard 'head-on' (e.g. ϑ = 0º). This means that the true mean P_{hit}, $P_{perforation|hit}$ and $P_{i|hit}$ values in the region 29º < ϑ < 39º are likely to be relatively underestimated when compared to ϑ = 0º.

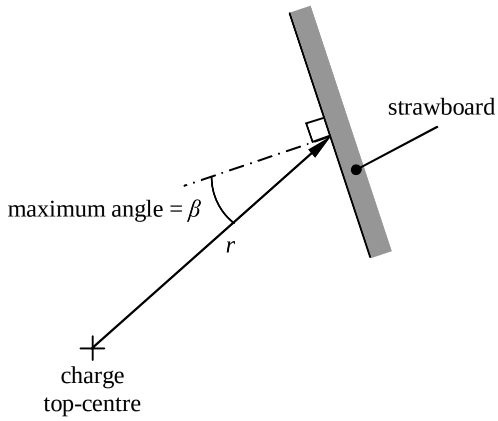


Figure 7.13: Definition of incidence angle, β

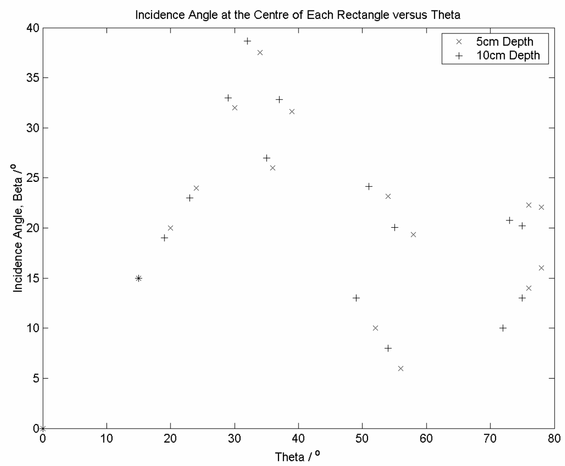


Figure 7.14: Incidence angle, β, versus angle from vertical, ϑ

Another effect of the trials geometry is that r varies between 0.80m and 1.09m (Figure 7.15) because the target is not hemispherical. If r is greater than 1m then the true mean P_{hit} values are underestimated, while the true mean $P_{perforation|hit}$ and $P_{i|hit}$ values are overestimated. The reverse is true if r is less than 1m. It is proposed that this is because the results are conditional on impacts being recorded: As r increases the proportion of stones with sufficient m and V_s to mark the strawboard decreases. This means that for the proxies of *MD* and *KED*, and the Kokinakis-Sperrazza variable, peaks are likely to occur at approximately 20º and negative peaks are likely to occur at approximately 55 and 75º. The peaks are likely to be reversed for P_{hit}.

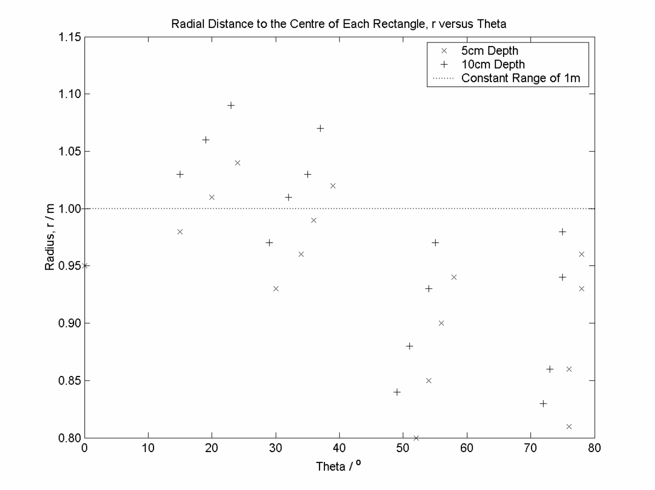


Figure 7.15: Radial distance, *r*, versus angle from vertical, ϑ

Another important source of error, as in the calibration, is the human judgement called on to identify permanent deformations of the strawboard. The same observer recorded all the perforation, penetration and witness mark depths to minimise the effects of human error.

7.6.6 Relationship with the protection subsystem of Chapter 6

The Five-stage model for estimating protection (Section 6.2.4) provides a framework for combining the knowledge gained in this chapter. Firstly, the likelihood of a buried AP blast mine occurring, $P_{occurrence}(\vartheta)$, is assumed to be 1. This enables comparison with blast and primary fragmentation from such a device because *occurrence* is the same for all threats. Secondly, $P_{hit}(\vartheta)$ predicts the *incidence* of secondary fragmentation. This allows a safer value of ϑ to be chosen – i.e. closer to ground level – illustrating *Feedback Loop 1*. Thirdly, *resistance* is estimated by a proxy for $P_{perforation|hit}(\vartheta)$. The results suggest that the likelihood of armour that is designed to protect against primary fragments resisting secondary fragmentation is 1. Given that the mine is assumed to detonate, *Feedback Loop 2* has no time to affect $P_{occurrence}$. Fourthly, a proxy for $P_{i|hit}(\vartheta)$ for the unarmoured wearer estimates the probability of *incapacitation (U)* as 1: Any exposed tissue facing will be injured. Conversely, the go-no go evaluation of *resistance* suggests that the probability of *incapacitation (A)* for a fully armoured person is 0: Any tissue covered by primary fragmentation armour will be uninjured by secondary fragments. Thus, *protection* for armour that defeats primary fragmentation is a function of the area of coverage. This analysis leads to the simplified conclusions: duck, wear armour that defeats primary fragmentation and cover up. More detailed conclusions are now presented.

7.7 CONCLUSIONS

1. Deminers are much safer approaching an AP blast mine in the prone position than in a squatting position as reported elsewhere (Trevelyan, 2000). In particular, the mean conditional values of $P_{hit}(X < \vartheta < 80°)$ are approximately 15% of $P_{hit}(0°)$, while $P_{perforation|hit}$ and $P_{i|hit}$ between X and 80° are 70% of their value at 0°. X is 23° for trial 1 and 30° for trials 2 to 8. Hence, the chances of armour being defeated or a person being incapacitated can be reduced by up to approximately 90%† solely by adopting safer tactics.

2. The most important conclusion for the armour designer is that, for the trials variables considered, impacts from primary fragments are likely to be more able to defeat armour than secondary fragments. If a garment already offers fragmentation protection, secondary fragments can be ignored.

3. If no protection is offered then the unarmoured person is likely to be wounded or killed by secondary fragmentation in addition to the blast threat. The designer can assess the relative importance of armour at different values of ϑ by multiplying the average number of hits per rectangle by the most appropriate choice of either the *MD* proxy or *KED* proxy.

4. The stones break up on impact with the strawboard. Therefore countermine and EOD suits should stop them more easily than tough metal fragments. However, other stronger and sharper stones (such as granite, flint or quartz) are potentially more dangerous. The calibration test outlined in Section 7.4.2 has the potential to test armour against individual, small fragments.

5. The method of firing used for calibration is versatile enough to allow a variety of fragment shapes, sizes, velocities and materials to be used. In this experiment velocities up to 860 ms^{-1} were achieved. The only limit for shape and size is the plastic wadding cup, which has a finite volume.

† $(1 - 0.15 \times 0.70) \times 100\%$

7.8 RESEARCH RECOMMENDATIONS

If each trial is repeated with pits of identical, spherical fragments of a known mass (e.g. steel ball bearings) then the single distribution of V_s can be calculated rather than the three separate models used in this analysis.

A major benefit to all arena trials would be achieved by developing a method of measuring the three-dimensional velocity of multiple, high speed fragments. A potential solution is to use combine multiple flash x-ray photographic shots from different directions over very small time steps. A computational algorithm such as those used in fluid dynamics would then be used to identify individual fragments. Their velocity is a function of their direction and distance travelled in the fixed time step.

Until such a three-dimension velocity measurement system becomes available, the strawboard panels can be calibrated for incidence angles greater than zero. This can be applied to the trials data using the spherical co-ordinates to improve the accuracy of the trials results.

The stones break up during an impact unlike the majority of metallic primary fragments used against personnel. Uniformly shaped ceramic balls (e.g. porcelain grinding balls) could be used instead of stones, to study the effect of fragment break up with less variability than the stones.

A standard method of identifying penetrations and witness marks would enable a more accurate method to be established.

7.9 REFERENCES

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CHAPTER 8: SUGGESTIONS FOR ERGONOMIC EFFECTIVENESS ASSESSMENT (SUBSYSTEM)

8.1 INTRODUCTION

8.1.1 Aims

To illustrate the ergonomic effectiveness subsystem elicited in Chapter 5, make suggestions for its assessment and support the development of the Mk 5 EOD Suit (Chapter 2.2.3).

8.1.2 Objectives

- Assess the operation of a novel demister for the Mk 5 EOD Suit,
- Discuss the choice of measures of ergonomic effectiveness,
- Propose the novel use of biomechanics software to assess ergonomic degradation.

8.1.3 Background

Ergonomic effectiveness is the change in the ability of a person to carry out their job as a result of wearing armour, within the context of use. It is the primary constraint of practical personal armour. This stems from the definition of personal armour in Chapter 1 as pertaining to "individual, man-portable… coverings… within the context in which they are to be used." The wearer bears the burden of armour as well as receiving the benefit of protection. It is vital that the designer can assess the degradation in performing tasks: can the wearer still do his job well enough?

Ergonomic design is demonstrated in Section 8.2 for the case of visor demisting. It shows that human factors issues are interlinked but can be balanced to minimise the degradation in ergonomic effectiveness, for a given level of protection. It also supports the Mk 5 EOD Suit development.

Once a personal armour design is conceived, its ergonomic burden on the system must be assessed. Chapter 3 illustrates that, presently, designs are gauged using metrics at different system levels. For example, areal density (weight per unit area), weight and time to complete, *TTC*, a task are used in materials assessment (Tobin, 1985), garment testing without a wearer

(Gotts, 1999) and garment testing with a wearer, respectively (Ashby et al., 2004). The choice of measures to assess ergonomic effectiveness is discussed in Section 8.3.

Overheating, reduced reach and wearer fatigue are three of the most significant degradation mechanisms due to wearing armour as described in Chapter 3. Developments in human factors simulation offer to the potential to predict the mechanical and thermal burdens of armour, before a garment is physically constructed. This is analogous to the way that CASPER (Hunting Engineering, 1999) is used to assess protection. Section 8.4 suggests how this could be achieved.

This chapter draws substantially from a conference paper by the author (Couldrick & Iremonger, 2000) and a draft proposal to DLO DC R&PS (Appendix C).

8.2 MK 5 EOD SUIT DEMISTER – AN EXAMPLE OF ERGONOMIC DESIGN

8.2.1 The issues of electrically heated visor demisting

Misting of Explosive Ordnance Disposal (EOD) visors is a significant problem. Bomb disposal personnel are unable to complete their task safely if they cannot see the device. The misting is due to exhaled breath and sweat condensing on the inner visor surface.

A demonstrator for an electrical heating system has been designed by Paul Calver of DLO R&PS to de-mist the visors of EOD personnel after consideration of alternative methods. It consists of a transparent, conductive film (Figure 8.1) that is placed at the inner visor surface (Figures 8.2 & 8.3). An electric current is passed across the film to heat it. Raising the visor's temperature prevents moisture from condensing on the surface and, therefore, stops misting.

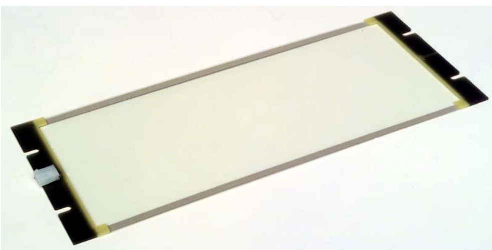

Figure 8.1: Demister element (picture courtesy of DLO DC R&PS)

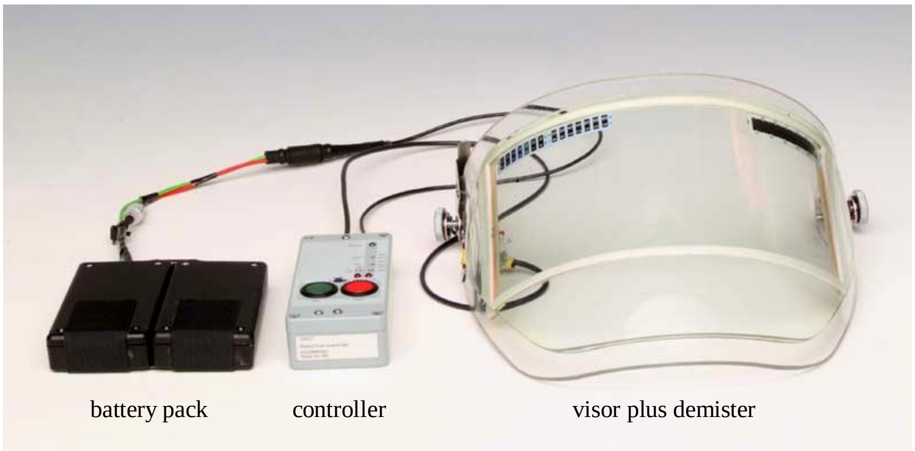

Figure 8.2: Assembled visor, demister element, controller & battery pack (picture courtesy of DLO DC R&PS)

Figure 8.3: Visor demister mounted on a Mk 4 EOD Suit helmet (picture courtesy of DLO DC R&PS)

The desired positive benefit is that the visor can be guaranteed to be mist-free for the duration of an EOD operation. The two key negative properties of the demister are that it increases the burden on the wearer of (i) weight – particularly of the batteries including spares – and

(ii) radiant heat from the visor. This section of the thesis demonstrates how ergonomic design can be used to balance the demisting performance while minimising these negative emergent properties. Recommendations are made for the following visor parameters: maximum required operating temperature, method of control, position of the heater element and mounting the element on the visor.

8.2.2 Maximum operating temperature

Ergonomic assessment for personal armour design requires that at least the wearer, armour, task and environment are considered (Chapter 5). The wearer is any sweating, breathing individual likely to wear the visor; the armour is the heat-insulating and moisture-resisting Mk 5 EOD Suit; the task is moving, crouching, etc. while carrying the 30kg suit and any equipment; the environment is anywhere that EOD work is undertaken down to sub-zero temperatures or at high humidity.

The heat balance equation (Equation 8.1) (Parsons, 1993) provides a starting point for a basic analysis. The metabolic rate, M, is high relative to an unarmoured person in order to exert greater work, W, because of the heavier, more restrictive load; and the heat losses through evaporation, E, convection, C, conduction, K, and radiation, R, are greatly reduced due to the insulation of the suit. The metabolic rate is always greater than the exerted workload because muscles are not 100% efficient, so the rate of heat storage tends to go up unless the thermoregulatory mechanisms of the wearer can increase the heat loss. Thus, the wearer's skin temperature (due to vasodilation), sweat rate and deep body temperature tend to increase. This agrees with experimental observations (Haisman & Goldman, 1974).

$$S = (M - W) - E - R - C - K \quad (8.1)$$

Misting occurs when moisture in the air condenses on the visor surface. This happens if the visor surface is below the 'dew point temperature' (Rogers & Mayhew, 1992) for the mixture of air and water vapour at the combination of temperature, humidity and pressure within the microclimate of the EOD suit. No misting will occur if the visor's condensation surfaces are kept above the dew point temperature.

The human body produces water vapour in evaporated sweat and exhaled air. The increase above atmospheric pressure in exhaled breath is negligible; and the human body cannot supersaturate air so the humidity is less than 100%. If the deep body temperature of the wearer is cooler than the suit's microclimate (due to external heating), then no misting will occur. If it is hotter, then that is the maximum temperature at which water vapour can be released from the human body. Withey (2001) states that "a rise of 2.0°C is dangerous and borders on a medical emergency because the thermoregulatory mechanisms begin to fail." There are more important things than misting to worry about if the wearer's core is over 39°C. Hence, *no misting will occur if the visor's condensation surfaces are kept at or above wearer's deep body temperature (up to 39°C).*

The definition of a maximum temperature provides design limits that guarantee mist-free vision. In practice, the visor can often be operated at a lower temperature because moisture dissipates into clothing and escapes to the atmosphere.

8.2.3 Visor demister control method

Two methods of controlling the heater element are considered: duty (time) cycle and temperature regulation. The first technique switches the element on or off for set periods of time. The second technique turns the element on when the temperature of the condensation surface drops below a set value. Both methods give the wearer some form of control to increase or reduce the de-misting power as required.

The advantage of duty cycle regulation is that the control circuit is discrete, whereas temperature control requires a surface-mounted, potentially vulnerable thermistor. However, the disadvantage is that the power supplied to the heater element is fixed, rather than related to the power required. This means that the wearer will spend too much time adjusting the duty cycle because the power needs vary with atmospheric conditions and time – as the visor reaches a steady state. Moreover, the wearer may try to compensate by raising the duty cycle above the required level, thus wasting electrical power and overheating the wearer.

Temperature control needs much less adjustment than time regulation because it relates the power supply to demand. Consequently, the element is more efficient and the wearer is less likely to overheat. The wearer only needs to reduce the temperature to a set level below 39°C to account for the dissipation of moisture to the atmosphere and clothing. For these reasons, *temperature regulation is preferable to duty (time) cycle control.*

8.2.4 Position of the heater element

Three positions on the inner visor surface are considered for the heater element: (A) in contact, (B) separated without a gasket, (C) separated with a gasket.

Position A (Figure 8.4) has the advantage of being the least bulky of the three choices. However, there is a relatively long rise time to reach the steady state because the visor must be heated before de-misting occurs. The higher thermal conductivity of the visor material – than still air – results in lesser de-misting efficiency.

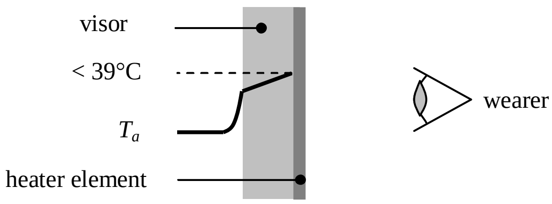

Figure 8.4: Visor & demister in contact (position A) superimposed with the steady state temperature gradient

Position B (Figure 8.5) has the heater element separated from the visor by a gap of 1 to 2 mm. This has the advantage of providing an insulating layer of air that reduces heat loss. However, moist air can become trapped in the gap and condense on the visor. Therefore, the visor surface – rather than the heater element – must be kept at up to 39°C to guarantee mist-free vision. Position B is less efficient and has a longer rise time than position A because both the air gap and the visor must be heated.

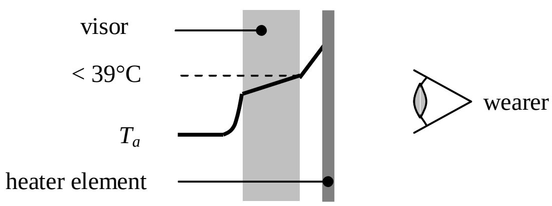

Figure 8.5: Visor & demister separated without a gasket (position B) superimposed with the steady state temperature gradient

Position C (Figure 8.6) is the quickest to reach the steady state and most efficient of the three arrangements, so uses least battery power. The heater element is separated from the visor as in position B but a gasket prevents moist air from condensing on the visor surface. No moisture can condense on the visor, so only the element needs to be at about 39°C to guarantee mist-free vision. The air gap provides a degree of thermal insulation to reduce heat loss. *Therefore, Position C (with the visor and heater element separated by an airtight gasket) offers the quickest demisting for the least energy consumption.*

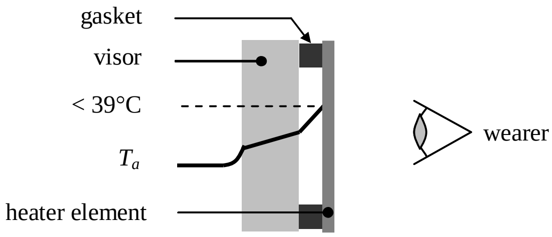

Figure 8.6: Visor & demister separated with a gasket (position C) superimposed with the steady state temperature gradient

8.2.5 Mounting the heater element on the visor

Care must be taken not to trap moisture between the heater element and the visor in order to guarantee mist-free vision. *The heater element should be mounted on the visor in a relatively dry environment.* In practice, if no condensation forms on the visor at the normal minimum operating temperature and pressure, the environment can be considered dry enough.

8.2.6 Ergonomic design minimises the system burden

A heated visor demister reduces the ability of the wearer to lose heat further, so the deep body temperature will rise quicker *ceteris paribus*. Eventually, the wearer will get too hot and have to stop work if not sooner. The demister does not provide a burden-free solution. However, putting it in Position C and controlling it by temperature regulation means that the burden is minimised. The element only consumes electrical energy and radiates heat when the alternative is likely to be that the wearer cannot do their job because of a misted visor. Thus, *ergonomic design minimises the degradation in ergonomic efficiency for a given level of protection.*

8.3 MEASUREMENT OF ERGONOMIC EFFECTIVENESS

8.3.1 The issues of measuring ergonomic effectiveness

The first step for a full Human Factors assessment is to specify the wearer, task and environment. It is necessary to describe the attributes of the wearer group (*Target Audience Description*) such as size, fitness, gender and age; task features e.g. range, rate and duration of movement as well as postures and typical actions; and environment factors including the temperature, humidity, other kit and clothing.

The second step is to define a reasonable test in terms of the desired level of information and the cost of carrying it out. This leads to three distinct stages of assessment during the development of body armour: materials assessment, garment testing *without* a wearer and garment testing with a wearer. Early in the design process, the measures are generic and could apply to any scenario. As the system becomes more defined, testing is more specific to the real outcome of wearing personal armour.

Calver (1995) states that the ergonomics requirements for the Mk 5 EOD Suit include "[armour] weight and [system] mobility." These are two separate levels of information because one can be estimated without the wearer and the other cannot. Contextual information must be supplied to interpret the requirements. Hence, there is a need for designers to make the difference between human factors assessment at separate system levels explicit.

The third step is to compare the results from different designs in terms of measures of effectiveness (MOE) and *not* measures of performance (MOP). This is akin to using the usefulness factor, *UF*, rather than the probability of incapacitation, P_i, to assess protection in Chapter 6. For example, the time to complete, *TTC*, a task with armour is an MOP. It does not help the designer or user decide whether this is good or bad unless it is compared the results for the unarmoured state. The MOE is the change in *TTC* for the armoured and unarmoured man. Therefore, there is a need to choose appropriate measures at each system level in order to compare one design against another.

8.3.2 Materials assessment

Materials assessment is used to select the most promising combinations and constructions of fabrics. At this stage the designer should consider materials that are multifunctional rather than only building up many single-purpose layers. The metrics shown below allow the properties of different materials to be compared.

Suitable MOEs for materials assessment are as follows.

- Areal density (mass per unit area) is an established (Tobin, 1985) criterion for comparing materials. Its basis is that it affects the weight of a garment, which affects musculoskeletal loading.
- Thermal and moisture resistances of materials are used (Congalton, 1995) because they influence the insulation of amour and, thus, the rate of heat storage.
- Flexibility of a material pack is measured (Missihoun et al., 1998) as a guide to understanding the flexibility of a garment and, hence, factors such as the mobility of the wearer.
- Friction coefficient at the skin contact at the appropriate humidity levels could be used to predict blistering and abrasions due to different materials.
- Thickness can be used to compare bulk in order to improve mobility and the use of other kit.

All of these measures may be considered as MOEs for a sub-subsystem level. They are MOEs because the unarmoured state is to have zero areal density, thermal & moisture resistance, coefficient of friction or thickness and infinite flexibility. They are at the sub-subsystem level because they mean nothing until they are constructed into armour that is worn and used.

8.3.3 Garment testing without the wearer

Garment testing without the wearer is carried out to select the most promising assembly. Repeatable, generic tests are carried out to assess the fully constructed prototypes, both before large-scale manufacture and before being put into the market place.

Suitable MOEs for garment testing without the wearer are as follows.

- Armour weight is a common predictor of the affect on the wearer. For example, Ashby et al (2004) show that it relates to the *TTC* infantry tasks (Figure 3.11). It is the combination of the material's areal density and garment's surface area.
- Thermal and moisture resistances of garments are assessed (Holmér, 1999) because their geometry influences the flow of heat and water-vapour around the armour. This affects the rate of heat storage.
- Structural flexibility or, conversely, stiffness is a function of the material flexibility and garment geometry. This links directly to mobility issues such as the range and rate of movement a wearer can achieve.
- Volume or bulk is the combination of the material's thickness and garment's surface area. It can be used to predict interference with the armour itself (during movement), the wearer (e.g. under arms) and the environment (e.g. doorways or other equipment).

These are all MOEs at the subsystem level. They are MOEs because the unarmoured state is to have zero armour weight, thermal & moisture resistance or bulk and infinite flexibility. They are at the subsystem level because they mean nothing until a person wears them to carry out a task.

The results of garment testing without the wearer give enough information to dismiss unsuitable options. Reducing the number of candidates facilitates finding armour that is likely to offer the minimum reduction in individual performance.

8.3.4 Garment testing with the wearer

Garment testing with the wearer is conducted to assess the ergonomic effectiveness of solutions as close as possible to the real scenario. A representative sample of wearers is asked to perform realistic tasks with other typical kit, preferably for the maximum duration that the armour is likely to be worn. This can be anything from an individual fitting for the civilian market that takes an hour, to an extended trials exercise for the military use that takes months (Edwards & Tobin, 1990). It can also include feedback from people using existing armour in the field (Dean & Newland, 2002).

Such trials must be carefully conducted to ensure that a statistically representative sample of system variables is used, e.g. the ages, sexes and sizes of wearers. The data collected can be objective or subjective.

Suitable objective MOEs for garment testing with the wearer are as follows.

- Change in *TTC* a prescribed task (Ashby et al., 2004, Kistemaker et al., 2004) is the temporal degradation due to wearing personal armour.
- Change in rate of oxygen consumption (Amos et al., 1998) is a predictor of the change in system failure by fatigue.
- Change in the number of errors (Widdows, 1991) is a measure of the affect on the quality of work carried out.
- Change in the rate of increase in the wearer's deep body temperature (Haisman & Goldman, 1974) is a predictor of the change in system failure by overheating (Withey, 2001).
- Change in reach or in workspace envelope (three-dimensional reach) is the spatial degradation due to wearing personal armour.

These are all MOEs at the system level. They are MOEs because the change in value compares the armoured and unarmoured states. They are at the system level because they can be understood as emergent properties of the system.

8.3.5 Using different measures for ergonomic effectiveness

Using a variety of MOEs at different system levels to compare armour is *not* wrong. However, the designer must make any decision maker aware of their differences by including sufficient depth in the system context.

Using MOPs is wrong because they are not comparisons of the armoured and unarmoured states. Nevertheless, measures such as weight and areal density are MOEs, for the subsystem and sub-subsystem respectively, because the unarmoured state is zero.

8.4 POTENTIAL FUTURE ASSESSMENT OF ERGONOMIC EFFECTIVENESS

Protection and ergonomic requirements are not the same for all parts of the body or all stages of a task. The head and torso are more vulnerable when attacked than the arms and legs, so need more armour. Shields can be picked up or put down depending on the threat level. Casualty reduction analysis software (e.g. CASPER) is already used to assess this variation of protection requirements as demonstrated in Chapter 6. Ergonomic requirements vary too. For example, elbows need more flexibility and less weight than the abdomen. Similarly, a wearer needs lighter armour in an assault role compared to sentry duty. These requirements can be incorporated into prototype garments that are constructed to undergo user trials. However, prototypes are costly to produce in terms of time and resources. A potential alternative for the future is to use computational models to simulate personal armour ergonomics in the same way that casualty reduction analysis tools are used to assess protection.

Biomechanics software is used widely to model the kinematics of the human body. If one inputs the dimensions of muscles, ligaments and bones, and muscular forces, it is possible to analyse human movement. Similar models are used to predict the effects of surgery when muscles are moved to compensate for injuries (Chadwick et al., 2001). If one tries to run a simulation in reverse by fixing the kinematics then the solution is indeterminate because there are many more muscle properties than there are degrees of freedom in human joints. Models such as SIMM (Delp & Loan, 1995) – developed originally by Stanford University – partially solve the problem by outputting joint torques rather than individual muscle forces. Importantly, a computational biomechanics analysis program named PAM-Comfort™ (ESI Group, 2000) uses an assumption on the way humans allocate muscular work to make the problem fully determinant.

PAM-Comfort™ incorporates the assumption that muscles share their burden in order to minimise the total workload (ESI Group, 2000). It is stated (Novacheck, 1998) that "It is generally accepted that one of the most important determining factors of the manner in which the individual moves is to maximise efficiency. In general, it is held that for aerobic, steady state conditions, one chooses movement strategies which are the most economical in regard to energy usage." This means that, provided muscle forces stay within injury limits, one can estimate the mechanical workload required to move or maintain a static posture with or without the burden of kit such as armour. This software is being used by the French military to assess soldiers' ability to maintain aiming accuracy of a new rifle for the FELIN (Rouger, 1999) project.

PAM-Comfort™ is a 'cutting-edge' tool and requires separate development for new areas of interest. There are not sufficient resources and time to carry this methodology forwards within the scope of this thesis. However, the ideas such as those given in Appendix C are presented as a basis for possible future work. Firstly, armour can be modelled now as a distributed weight, with zero bulk and infinite flexibility. This has the potential to simulate the most important ergonomic consideration in the history of personal armour: How does changing the weight distribution of armour affect the wearer? Secondly, the model can be extended to include flexibility and bulk. A small-scale study based on one of the simpler yet useful joints – the elbow – can be extended to the whole body. An initial model of an armour sleeve, such as those of EOD suits, can offer an insight into a real application. Thirdly, PAM-Comfort™ itself can be developed to include a biothermodynamical aspect to the model.

A novel development of biomechanical tools would be to apply efficiency properties to the simulated muscles in order to produce a biothermodynamical model. The primary function of muscle is to generate force, which integrates with respect to time to become the mechanical workload. This is the variable that is estimated by PAM-Comfort™. However, muscles are not 100% efficient so they produce heat as a by-product (Wilkie, 1976, Aidley, 1989). If representative muscle parameters are built into the model, it should be possible to predict the heat generated in order to complete a task with and without armour. Then, together with the thermodynamic properties of clothing and the environment, such a model could be employed to estimate the rate of heat storage by using the conceptual heat balance equation (Equation 8.1). This would provide a prediction of a wearer's deep body temperature as a function of task duration, which links to changes in ergonomic effectiveness.

The development of a biomechanical and biothermodynamic model of the personal armour design system is beyond the scope of this thesis. The suggestions are given to highlight the potential for future work to aid the prediction of three important ergonomic constraints of personal armour: reduced movement, fatigue and overheating.

8.5 CONCLUSIONS

1. Ergonomic design minimises the degradation in ergonomic effectiveness due to wearing personal armour, for a given level of protection. It does not eliminate the burden. It balances the system with the aim of letting the person do their job as well as possible.

2. The Mk 5 EOD Suit electrical demister should be mounted in a dry environment and spaced from the visor by a gasket. It should be temperature regulated to a maximum of 39ºC.

3. Ergonomic effectiveness is measured in three stages: materials assessment, garment testing without the wearer and garment testing with the wearer. The designer must make any decision maker aware of the system level at which armour is assessed; and include sufficient depth in the system context for measures to be useful.

4. MOEs should be used rather than measures of performance (MOPs) because they are comparisons of the armoured and unarmoured states.

5. Weight is an MOE at the subsystem level. It is therefore a simplistic measure that can be used as a proxy for the ergonomic effectiveness of the system.

6. Computational biomechanical models have the potential to be reversed in order to calculate the muscular burden due to wearing armour. These could be used to predict the system degradation due to fatigue and reduced reach. This reduces the need to construct real prototypes and test garments with suitable wearers.

7. A biothermodynamical model could be developed from a biomechanical one. This would use muscle efficiencies to relate the work exerted by muscle to the heat generated.

8.6 RESEARCH RECOMMENDATIONS

There are many different ergonomic degradation mechanisms just as there are a multitude of incapacitation methods. However, there are a variety of measures of ergonomic effectiveness, whereas protection can be combined into a single metric for a given level of incapacitation. If it is assumed that the system user is only interested in whether a wearer can still do their job well enough, then it should be possible to combine the various measures together. The change in a measure such as the mean time to failure, *MTTF*, as a result of wearing armour – for a specified set of wearers, tasks and environments – could be used to relate different system failure mechanisms to a single measure. This assumes that it does not matter why the wearer cannot do his task; only that he cannot. It is used to predict the probability of achieving a mission (Knezevic, 1993). Hence, it is recommended that further research is carried out on unifying measures of ergonomic effectiveness.

Biomechanical and biothermodynamical simulations offer the potential to assess a greater variety of garments than can be built as prototypes. This is akin to the use of CASPER to assess protection without destroying a garment (and wearer) every time. It is cutting edge technology that is on the verge of becoming a sensible option for designers. Further research should be conducted to (i) build models of armour into and (ii) verify the use of muscular efficiency in PAM-Comfort™.

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CHAPTER 9: SYNTHESIS & OPTIMISATION OF PERSONAL ARMOUR DESIGN (SYSTEM)

9.1 INTRODUCTION

9.1.1 Aims

To build on the lessons learnt in Chapters 5 and 6 by developing theory and tools to synthesise personal armour design, in order to deselect solutions that do not offer the 'best possible protection.' This allows the designer to reduce the number of options, so that the customer is positioned better to make the ultimate choice of which armour is best.

9.1.2 Objectives

- Develop methods of trading off the benefits and penalties of any personal armour,
- Demonstrate the adaptation of casualty reduction analysis software to synthesise personal armour design for optimisation.

9.1.3 Background

The concept of '*best possible protection*' is based on the idea that any material has negative attributes such as a high price or areal density (weight per unit area). It is not possible to continue adding armour indefinitely: no garment can provide absolute protection from all threats so there must be trade-offs to balance.

This chapter compliments the qualitative description of the personal armour design system (Chapter 5) with a quantitative approach to personal armour optimisation for two reasons. Firstly, part of the designer's job is to measure or estimate the benefits and penalties of wearing armour as far as is reasonably practicable, in order to justify trade-off decisions. Secondly, as knowledge of the natural world increases it becomes easier to model the system and make useful predictions.

Chapter 5 clusters the benefit of personal armour into a subsystem named 'protection'; the major constraints faced by the designer are grouped into ergonomic and cost effectiveness subsystems. Each benefit and constraint is described by emergent properties that are traded off in this chapter.

Chapter 6 provides a suitable measure of effectiveness for protection called the usefulness factor, *UF*. This is defined as "the reduction in P_i for a given incapacitation criterion, after any reasonable reduction in incidence, due to wearing armour within the context of use." The key equation for this is repeated as Equation 9.1.

$$UF = P_{i\ unarmoured} - P_{i\ armoured} \tag{9.1}$$

The usefulness factor is developed in this chapter and the concept of a *protection optimisation envelope* is introduced, to deselect armours that do not offer the best possible protection. This leaves a limited selection of optimal solutions at the boundaries of possibility for the armour designer to discuss with the customer.

A theoretical military scenario is chosen in order to demonstrate the two concepts. Eleven theoretical armours are derived from a single initial material. CASPER (Hunting Engineering, 1999) is then used to synthesise the scenario with each armour. This provides a basis for discussing the advantages and disadvantages of both concepts for optimisation. Additionally, it demonstrates how CASPER can be developed to provide weight and cost – as well as protection – estimates for armour.

This chapter draws substantially on a conference paper by the author (Couldrick et al., 2002) that is supplied in Appendix D.11.

9.2 THEORY

9.2.1 Pseudo-optimisation of the protection subsystem: *UF**

The first method of quantitative personal armour design is to use *UF**. This is henceforward defined as the reduction in the P_i due to wearing a given section of armour. It is the usefulness of each piece of the garment, as given in Equation 9.2.

$$UF^* = P_{i,\ without\ armour\ section} - P_{i,\ with\ armour\ section} \tag{9.2}$$

If the designer is able to distinguish between the sections of armour that offer the greatest protection, *ceteris paribus,* he or she can build an optimum whole body solution. However, it does not matter when, where or how a person is incapacitated. If a person is guaranteed to die from a head wound, blast injury or when the garment is doffed, no amount of fragmentation protection over the chest is useful. Conversely, if the rest of the body is always protected absolutely, against all threats then the wearer's life depends solely on that single piece of armour. Hence, UF^* varies according to the protection afforded by the rest of the garment. The minimum occurs when the wearer is unarmoured except for the section under consideration. The maximum is the result of wearing the best possible protection except for the section under consideration. If the difference between the minimum and maximum is relatively small compared with the average value, then UF^* can be used to identify the armour sections that offer the most protection.

9.2.2 Optimisation of the protection subsystem: protection optimisation envelope

The second method of quantitative personal armour design is to use the concept of a *protection optimisation envelope*. This is the boundary that defines the maximum possible *UF* – as defined in Chapter 6 – for a given combination of ergonomic and financial constraints. It shows the best armour solutions that are available. The method of producing and using a protection optimisation envelope are described below.

Each armour design and pattern of usage (when to don and doff parts of the garment) has an associated level of protection, ergonomic penalty and financial cost. These form a cloud of possible solutions as shown in Figure 9.1. This diagram is presented in three dimensions but could be extended to include – although not graphically represent – any number of constraints such as total weight, rate of heat storage, time to wearer fatigue, etc. The main point to note is that not all solutions are sensible.

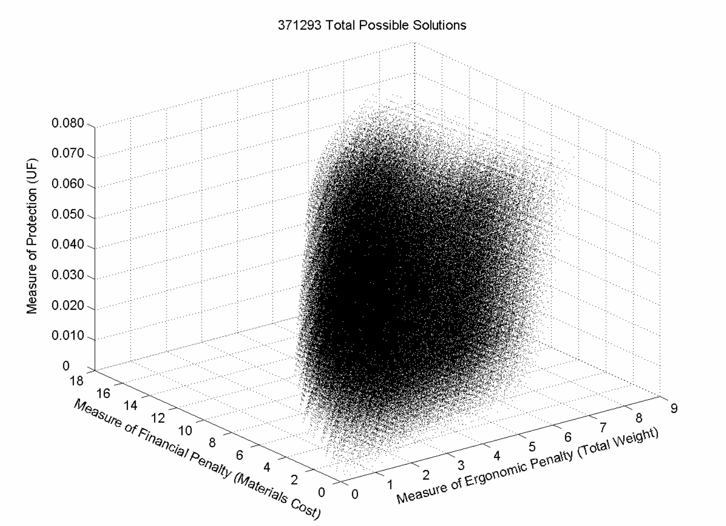


Figure 9.1: Total possible armour solutions form a cloud

Figure 9.1 presents 371,293 armour options that are generated later in this chapter. However, only some of them are shrewd choices. The next step is to filter out the unwanted ones. This is achieved by comparing each point to the others. If an armour option represents the maximum *UF* (Equation 9.1) at or under its ergonomic and financial constraints (shown here as total material cost and total weight) then it is retained; otherwise it is rejected. In this case, 1,448 solutions that give the 'best possible protection' are found. This method of optimisation is reasonable for the armour designer to apply in isolation because there is no bias of the constraints. The result is a protection optimisation envelope.

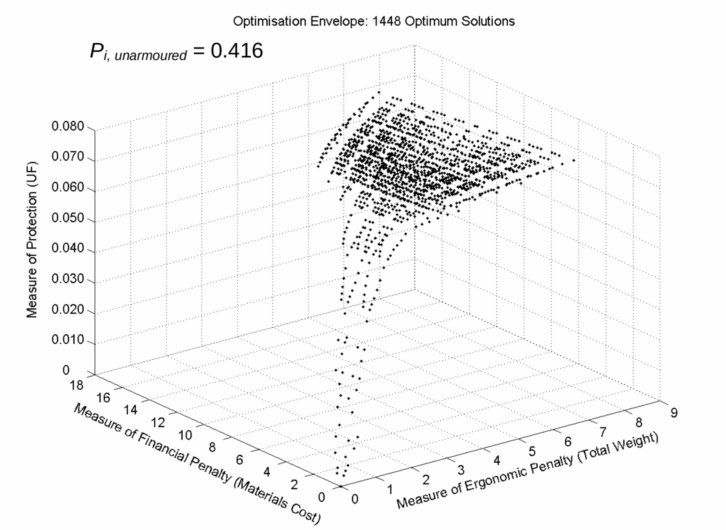


Figure 9.2: Protection optimisation envelope

The points in Figure 9.2 hold all the information necessary to trace the solution back to the original design (material, coverage, etc.). The envelope can be studied visually to identify ergonomic and financial combinations that are not possible using the available materials. If necessary, the value of $P_{i\ unarmoured}$ can be used with *UF* to identify the resultant probability of incapacitation. Most importantly, it draws attention to the regions of greatest increase in protection for the least constraint penalties. This is now a tool that armour designers and other interested parties can use to visualise and discuss personal armour solutions.

An optimisation envelope is the set of best possible, unbiased solutions. If conditions are applied by the wearer, purchaser or operations analyst then a smaller set can be obtained. If e.g. the relative costs and weights in Figure 9.2 are limited to less than 6 and 3 respectively, then a subset of solutions are obtained as shown in Figure 9.3. This type of condition must not come from the designer because it biases the constraints.

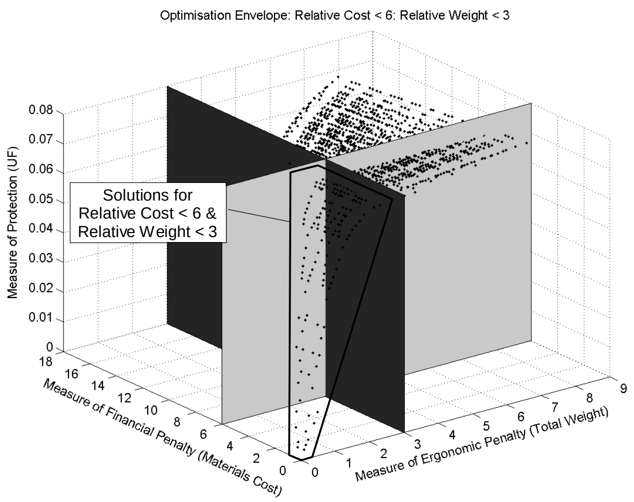
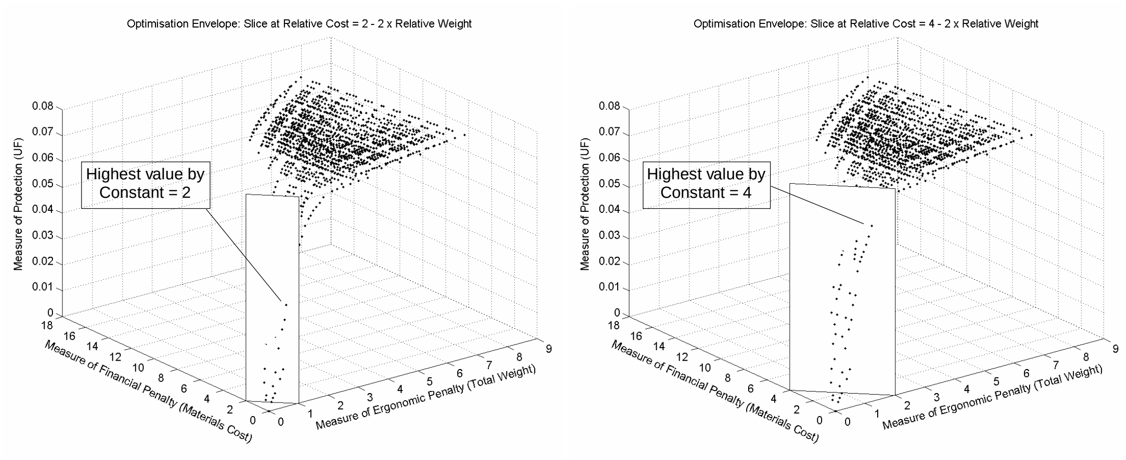


Figure 9.3: Protection optimisation envelope: relative cost < 6 and relative weight < 3

Another example of a constraint is to say that weight is twice as important as cost; then the best option can be found on each plane corresponding to cost + 2 × weight = constant. This is demonstrated in Figures 9.4a and b. Any increase of the constant must be associated with an increase of *UF*. Figure 9.4 a shows the maximum protection by constant = 2. Figure 9.4b illustrates the maximum protection by constant = 4. This information is used to build up a *constrained optimisation envelope* in Figure 9.5.



Figures 9.4: Protection optimisation envelope with slices corresponding to relative cost = constant - 2 × relative weight for (a) constant = 2 and (b) constant = 4

In Figure 9.5, the optimum armours are found for the stated condition of cost + 2 × weight = constant. In this case, the 371,293 possible solutions are reduced to 21 different options. Each point is a constrained optimum: the 'best possible protection' for the stated conditions and constraints. Each one can be traced back to the original design (material, coverage, etc.). For example, three interesting solutions are highlighted in Figure 9.5. The user, purchaser or operations analyst is able to use the measures of protection, ergonomic and financial cost effectiveness to estimate the contribution of armour to tactical success.

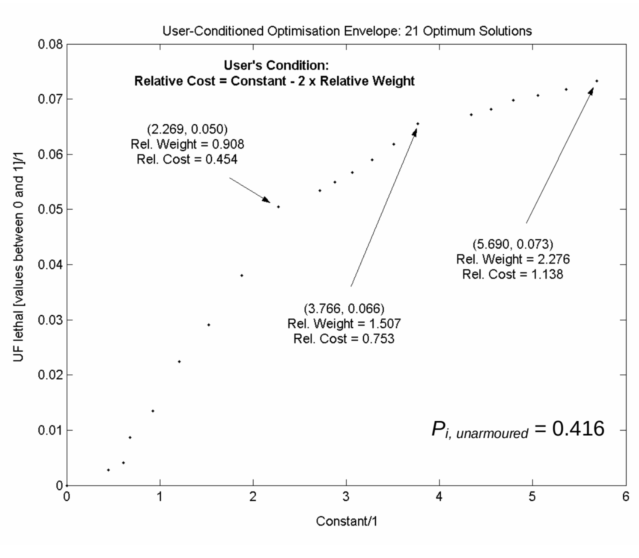


Figure 9.5: Constrained optimisation envelope

9.3 METHOD

9.3.1 Scenarios

The scenarios are that of a standard NATO crouched man (NATO, 1995) as given in CASPER (Hunting Engineering, 1999). His environment is the floor plane he is standing on, which offers no shielding. There is a single, stationary grenade (either a No. 36 Mills, an L2A2 or a 0.5 probability of each) placed on the floor at a horizontal range of 2m, which will detonate. It has an equal probability of detonating at any given angle around the man. The grenade's axis is normal to the floor plane with the fuse at the top (illustrated in Figure 9.6). Although a grenade is unlikely to adopt this orientation in real life, due to its centre of gravity, the calculations are simpler since fragments are distributed axisymmetrically. The man's task is to remain stationary with respect to the grenade. This means that there is no modification of any of the three sets of $P_{occurrence}$, so the analysis only needs one iteration.

The man's armour is an impenetrable helmet plus visor and a penetrable body suit that does not include the hands or feet. The use of impenetrable head protection simplifies the example by removing the need to consider helmet and visor materials. In a realistic situation the designer cannot ignore this since, if a person is certain to die by a head injury, no armour is useful. The body protection covers five different regions as defined in the *lethal* and *serious* (requiring hospitalisation) summarised Kokinakis-Sperrazza incapacitation criteria (Waldon et al., 1969): the thorax, abdomen, pelvis, arms, legs. Hence, there are six scenarios with two incapacitation criteria and three sets of $P_{occurrence}$. Overall, the scenarios are simplistic but they enable demonstration of *UF** and the protection optimisation envelope.

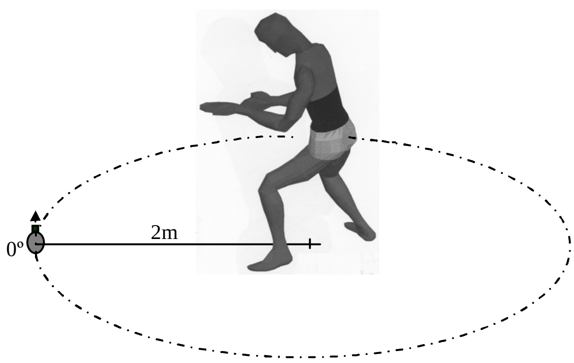


Figure 9.6: An unarmoured, crouched person 2m from a vertical grenade

9.3.2 Armour options

Six different protection levels are considered for two different materials (*a* or *b*). This gives a choice of twelve different armours plus the option of remaining unarmoured. Any of these can be used on the thorax, abdomen, pelvis, arms and legs. This gives a total of 371,293 (i.e. 13^5) possible armour options.

The initial protection level is based on a real, layered, soft, ballistic armour that is already modelled in CASPER. It has specified strike velocity versus residual velocity (V_s-V_r) profiles for four different fragment masses. These are extrapolated to give the characteristics of five theoretical protection levels. Briefly, the V_s-V_r profile identifies a limit velocity (V_L) above which the projectile has a residual velocity based on Newtonian conservation of energy. This is represented as:

$$V_r = 0 : V_s < V_L \tag{9.3}$$

$$V_r^2 = V_s^2 - V_L^2 : V_s > V_L \tag{9.4}$$

If the limit velocity for each projectile is increased then it is possible to define the V_s-V_r profiles for the new materials. In real life this may not be wholly true (e.g. if the projectile deforms) but it is a reasonable assumption for the creation of theoretical demonstrative armours. Appendix D.2 contains the materials properties used in the simulation. This information is saved for each armour in materials file format that is used by CASPER.

The theoretical armours are also given areal density (ρ_A) and cost per unit area ($\$_A$) properties relative to those of the initial material. It has been found (Tobin, 1985) that, for a given fragment and fibre-reinforced plastic armour, $V_{50} \propto \sqrt{(\rho_A)}$, where V_{50} is the statistical mid-point of estimates of a V_L. Hence, despite the differences between fibre-reinforced plastic and soft, layered ballistic armours it is reasonable to assign relative areal densities to the theoretical armours using the following equation for each material (*a* or *b*).

$$\rho_A \propto V_L^2 : \text{material } a \text{ or } b \tag{9.5}$$

It is reasonable to assume that the purchase cost per unit area of a material is relative to its areal density. Thus, the relative costs per unit area of the theoretical armours are given from the following equation for each material (*a* or *b*).

$$\$_A \propto \rho_A : \text{material } a \text{ or } b \tag{9.6}$$

In order to complete definition of the theoretical armours relative to the initial one, it is necessary to specify the cost per unit area and areal density of material *b* relative to material *a* for a given protection level. If material *b* is defined as being 90% of the weight but four times as expensive as material *a* to achieve the same protection, the following table of relative material properties can be drawn. The actual values used in the simulation are presented in Appendix D.3.

Code	**U**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Material	–	a	a	a	a	a	a	b	b	b	b	b	b
V_L	0	1	1.2	1.4	1.6	1.8	2	1	1.2	1.4	1.6	1.8	2
ρ_A	0	1	1.4	2.0	2.6	3.2	4	0.9	1.3	1.8	2.3	2.9	3.6
$\$_A$	0	1	1.4	2.0	2.6	3.2	4	4	5.8	7.8	10.2	13.0	16

Table 9.1: Properties of theoretical armours relative to armour A

9.3.3 Area of armour using CASPER geometry as a template

Geometry data from CASPER is used to define the surface area of the thorax, abdomen, pelvis, arms (excluding hands) and legs (excluding feet). This is used to calculate the total mass and cost of armour required to cover each of the five body regions. The source data is taken from CASPER's representation (Riach, 1997) of the NATO draft standard 'standing man' (NATO, 1995). The geometry of the man – rather than the armour – is used because it is divided clearly into Kokinakis-Sperrazza's body regions (Figures 9.7a, b & c). A standing – rather than crouched – man is used for two reasons. Firstly, the undeformed surface area of the body is calculated. This is the shape personal armour is designed to fit originally. Secondly, it simplifies the transformation of the CASPER geometry file into a surface area estimate. CASPER represents the human body as divided into triangulated sections or 'boxes'. For the standing man, the planes between sections are normal to CASPER's y- or z-axes. The three-dimensional co-ordinates of each node on the surface of a box are given in a geometry file. This file can be opened in a spreadsheet such as Microsoft Excel® 2000 in order to convert the co-ordinate data into a surface area (see the method presented below).

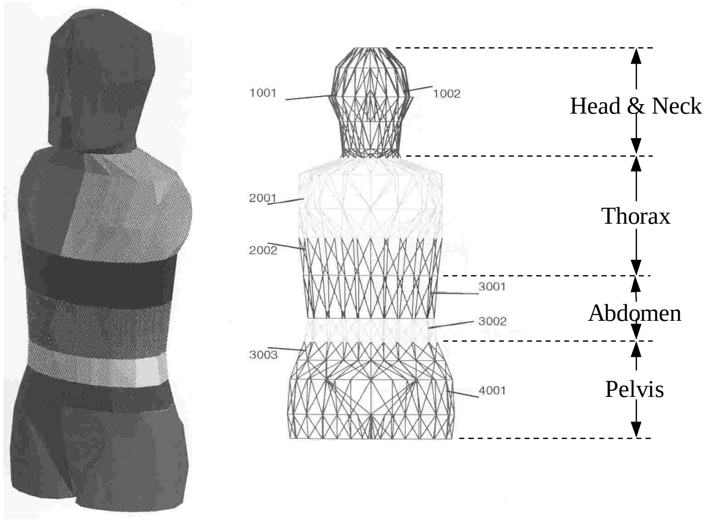


Figure 9.7a: Upper body regions (after Riach, 1997)

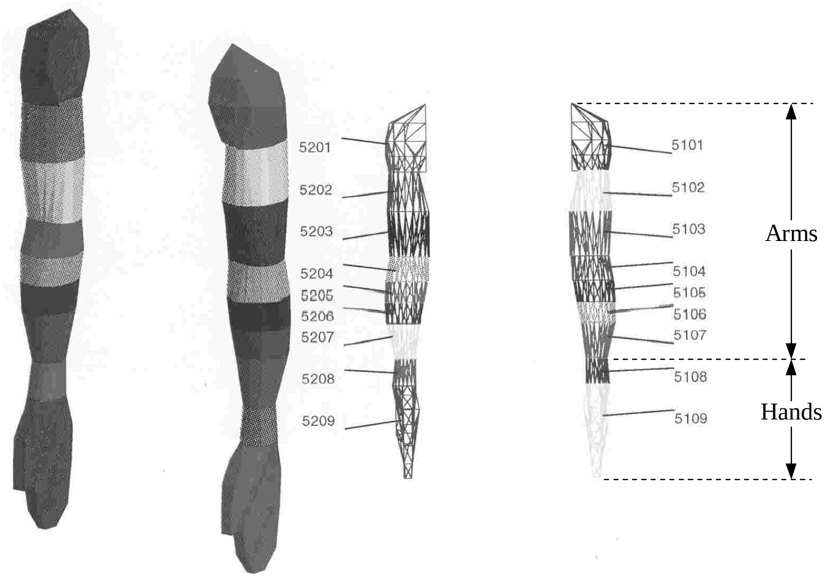


Figure 9.7b: Upper limb regions (after Riach, 1997)

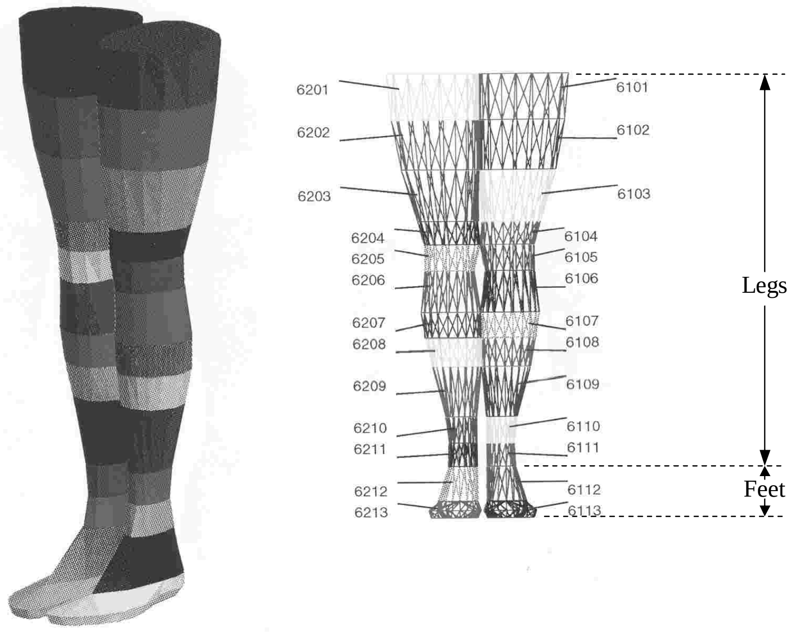


Figure 9.7c: Lower limb regions (after Riach, 1997)

The surface of the body modelled in CASPER is made up of triangles. Three-figure coordinates (in mm) of the corners of each triangle are given in CASPER's *.geo files. These can be used to calculate the surface area of the body. For example, Figure 9.8 shows a triangle in three dimensions with corners at points P_1, P_2 and P_3 and sides S_1, S_2 and S_3.

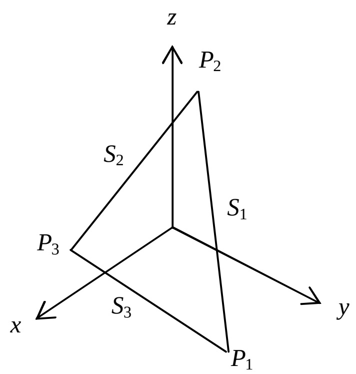


Figure 9.8: Demonstration surface triangle

The points are listed sequentially in the relevant *.geo file as:

$$P_1 = (x_1, y_1, z_1), \quad P_2 = (x_2, y_2, z_2), \quad P_3 = (x_3, y_3, z_3) \tag{9.7}$$

The sides are found using Pythagoras' theorem in three dimensions:

$$\begin{aligned} S_1 &= \sqrt{(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2} \\ S_2 &= \sqrt{(x_3-x_2)^2+(y_3-y_2)^2+(z_3-z_2)^2} \\ S_3 &= \sqrt{(x_1-x_3)^2+(y_1-y_3)^2+(z_1-z_3)^2} \end{aligned} \tag{9.8}$$

The area is then found using:

$$Area = 0.5S_3\sqrt{S_2^{\,2}-\left(\frac{S_3^{\,2}+S_2^{\,2}-S_1^{\,2}}{2S_3}\right)^2} \tag{9.9}$$

Care must be taken to exclude triangles that form boundary surfaces between contacting boxes when these formulae are applied to the CASPER *.geo files. For example, Figure 9.7a shows a flat surface where the arm attaches to the thorax. This is not a real body surface so must be excluded. If the standing man file is used, it is relatively simple to identify the contacting surfaces because they lie exactly in either the *x-y*, *x-z*, or *y-z* planes. In other words, P_1, P_2 and P_3 all have the same value of *x* or *y* or *z*.

The surface area of each of the CASPER body region is given in Table 9.2.

Region	Area/m^2
Thorax	0.227
Abdomen	0.150
Pelvis	0.192
Arms	0.459
Legs	1.001

Table 9.2: Surface area of body regions

9.3.4 Simulation and optimisation

CASPER is a casualty reduction analysis model that simulates the effects of fragmenting munitions on a target. It calculates the position and relative velocities of each fragment from an exploding device. The action of any garment or shielding is included before the effects on the person are determined. $P_{i|occurrence}$ with and without armour is then calculated using the summarised Kokinakis-Sperrazza criteria (Waldon et al., 1969). A more detailed explanation of the theory behind CASPER is described in a DCTA report (Grout, 2000) or in Chapter 3.

CASPER is used to simulate the given scenario with either the L2A2 or No. 36 Mills grenade in a single run. The equal probability of a device detonating at any angle around the man is approximated by averaging $P_{i|occurrence}$ at every 45° increment. A simulation run is required for each armour. There are 2 threats and 12 different armours (excluding the unarmoured option). Therefore, 24 simulations runs are carried out based on the variables presented in Appendix D.1.

The output from each simulation run is a text file that contains the values of $P_{i|occurrence}$ for each incapacitation category, body region and 45° increment. A spreadsheet (Microsoft Excel® 2000) is used to collate the files, remove extraneous information and calculate the averages. The resulting output is a table of $P_{i|occurrence}$ values for each threat of incapacitation category, armour (including the unarmoured option) and body region (see Appendix D.4). These are multiplied with $P_{occurrence}$ (0, 0.5 or 1) to obtain a table of P_i values for each armour section.

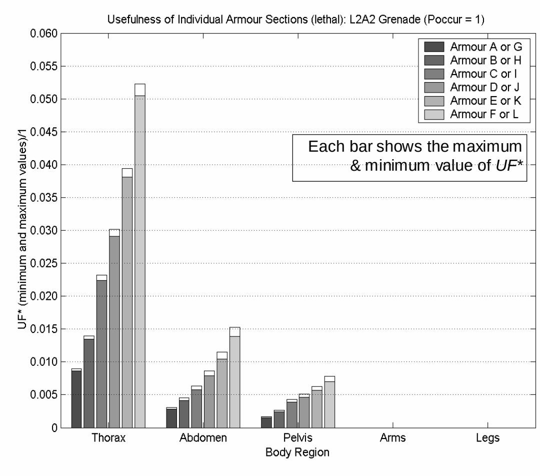
*UF** is relatively simple to calculate using Equation 9.2 because only two values (the maximum and minimum) are required for each armour section. A suitable routine is introduced in Appendix D.9. Thus, only 120 points are needed (12 armours × 5 body regions × 2). This is reduced by half due to the identical protective properties of materials *a* and *b*. Appendix D.10 presents a Matlab® M-file to produce a graphical output of the values.

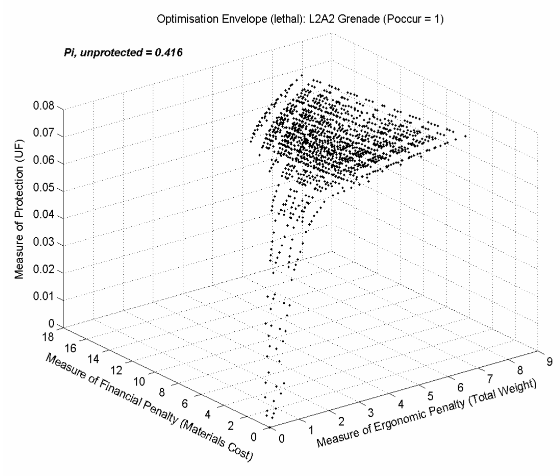
Conversely, the protection optimisation is too large to compute in Excel® so Matlab® 6.1 is used. *UF*, Total Weight and Total Materials Cost are generated (see Appendix D.5) for each of the 371,293 armour solutions. *UF* is calculated using Equations 6.2 and 6.3. There is no need to use Equation 6.4 because $P_{occurrence}$ remains constant with respect to time. Total Weight and Total Materials Cost are found by summing the multiples of Area and ρ_A or $\$_A$ respectively (given in Tables 9.1 and 9.2). Afterwards, the optimisation algorithm (Appendix D.6) compares each point against all of the others i.e. 137,858,120,556 checks. Although this is not efficient it is the most accurate method of obtaining a protection optimisation envelope. Appendices D.7 and D.8 introduce Matlab® M-files for user-constrained optimisation and tracing individual points back to their source, respectively.

9.4 RESULTS

Once the CASPER simulation results have been imported into Excel® or Matlab®, the graphs of *UF** are produced in a matter of minutes. However, generating the optimisation envelope for each scenario takes around 20 computer-days on a 2002 standard personal computer (e.g. Pentium 4 1GHz). The protection optimisation envelope and a theoretical user-constrained optimisation envelope (for cost + 2 × relative weight = constant) are now presented, together with graphs of *UF** for each scenario.

9.4.1 L2A2 Grenade ($P_{occurrence}$ = 1), Lethal





Figures 9.9a & b: Lethal *UF and optimisation envelope for an L2A2 grenade ($P_{occurrence}$ = 1)**

UF* (Figure 9.9a) shows clearly that, for the lethal incapacitation criterion, it is most important to protect the thorax. The next most important body region is the abdomen. However, this has to have at least armour levels E or F (or K or L) to offer as much protection as can be obtained on the thorax. The last consideration is to protect the pelvis. Moreover, it would seem that the arms and legs should not be protected at all. This is because the Kokinakis-Sperrazza lethal incapacitation model does not count injuries to the limbs.

The protection optimisation envelope (Figure 9.9b) demonstrates that there are 1,448 optimum armour solutions. However, the final choice depends upon the customer's prioritisation of protection, ergonomic and financial cost effectiveness. There is a sharp rise in protection where the relative weight and cost are less than 3 and 6 respectively. Afterwards, the rise in protection is much shallower. This is due to the best armour solutions being combinations of armour levels on the thorax, abdomen and pelvis. The shallow rise section reflects the addition of leg and arm protection. This is counted in this model because there is a small chance that fragments may penetrate the arms or legs and enter the pelvis or torso, which *UF** does not show.

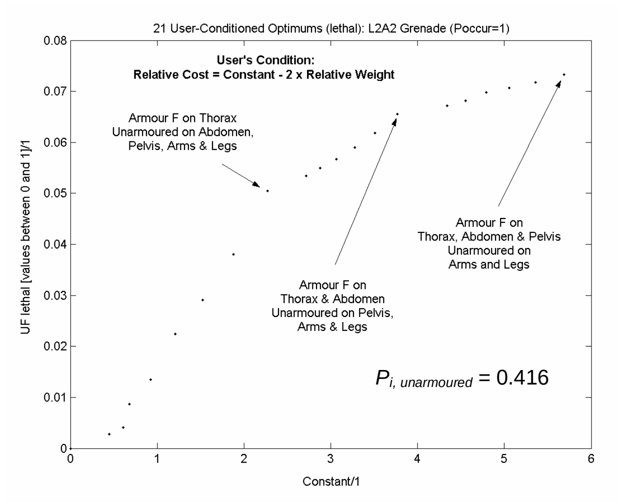


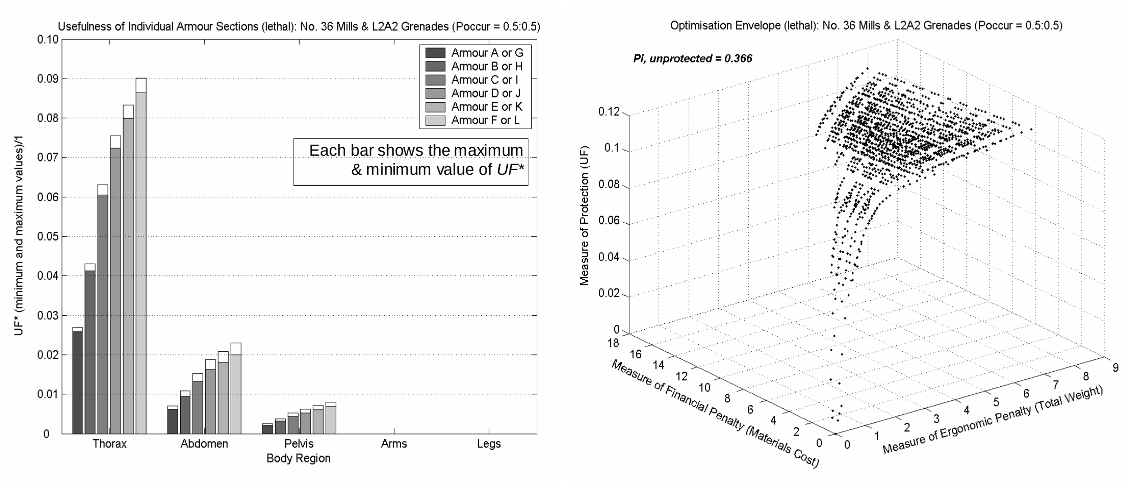
Figure 9.10: Lethal constrained optimisation envelope for an L2A2 grenade ($P_{occurrence}$ = 1)

The user-constrained optimisation envelope (Figure 9.10) highlights 21 solutions for the condition that weight is twice as important as cost. Three interesting points are selected: two where the gradient changes and one at the maximum possible protection. These show that, under this condition, it is a good idea to cover – in priority order – the thorax, abdomen and pelvis with armour F. This fits very well with the knowledge gained using *UF**.

Either optimisation envelope can be used to identify that the maximum protection possible in this scenario is $UF_{lethal} \approx 0.07$. In other words, it is expected that 7 percent of people in this scenario who would otherwise die, can be saved. Whether this is a big enough benefit for the weight and cost penalties if for the user, purchaser, commander or operations analyst to decide.

9.4.2 36 Mills & L2A2 grenades ($P_{occurrence}$ = 0.5:0.5), lethal

Figure 9.11a show that it is even more important to protect the thorax against a 50-50 chance of either an L2A2 or a No. 36 Mills grenade detonation than for a guaranteed L2A2 explosion. No considered armour on any other area of the body can offer as much protection. Moreover, the values of *UF** indicate that armour can offer more defence against the No. 36 Mills grenade than the L2A2 device. This is unsurprising because the later is more modern and a better weapon than the former.



Figures 9.11a & b: Lethal *UF and optimisation envelope for No. 36 Mills ($P_{occurrence}$ = 0.5) & L2A2 ($P_{occurrence}$ = 0.5) grenades**

This protection optimisation envelope (Figure 9.11b) also demonstrates a sharp rise in *UF*, for the same reasons as before. One of the useful features of this type of diagram – especially if viewed from above – is that it is simple to identify combinations of constraints that are not possible. For example, no matter how much money one spends over a relative price of approximately 4, there is no armour that has a relative weight less than about 2.

In Figure 9.12 the 1,507 optimum points are whittled down to 29 user-constrained solutions. The first highlighted point is for armour E on the thorax only. More importantly, it is not armours F or L on the thorax. This level of selection is not possible without using constraints. It is possible to compare *UF** without considering the ergonomic and financial costs of choosing a particular armour section. However, it is wise to bear in mind the constraints even if only as a qualitative discussion from the designer's experience.

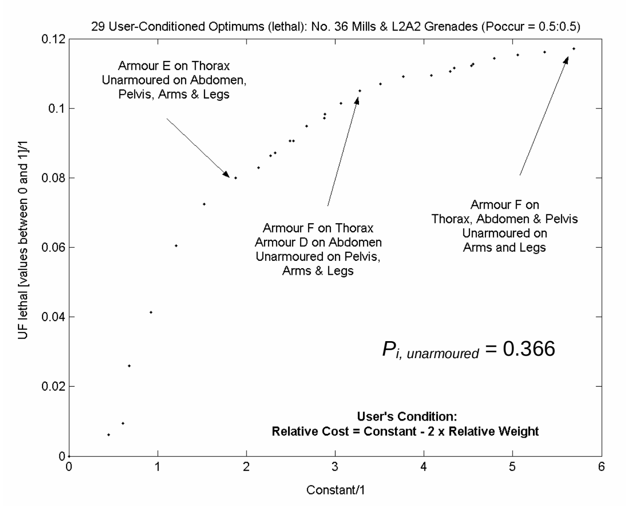
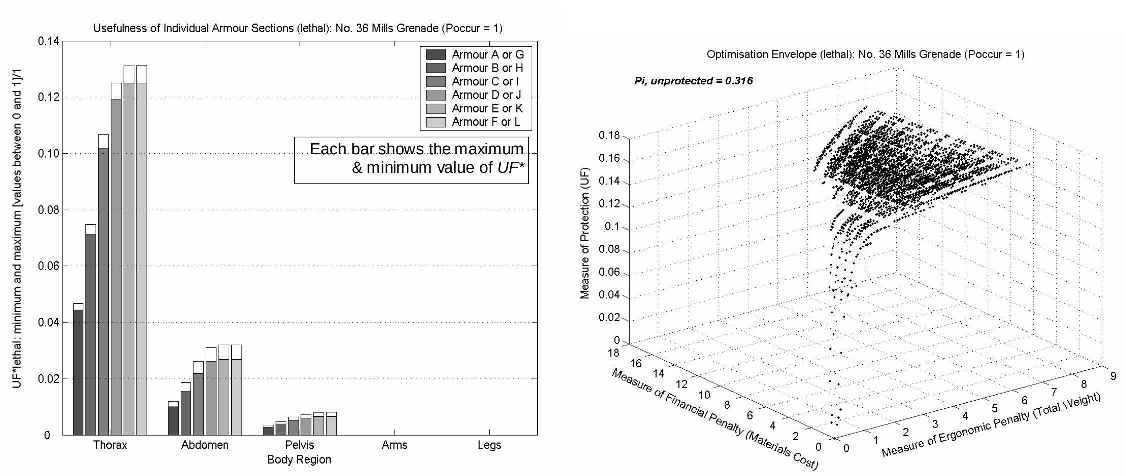


Figure 9.12: Lethal constrained optimisation envelope for No. 36 Mills ($P_{occurrence}$ = 0.5) & L2A2 ($P_{occurrence}$ = 0.5) grenades

9.4.3 36 Mills grenade ($P_{occurrence}$ = 1), lethal

The graph of *UF** (Figure 9.13a) presents a small increase in the tolerances associated with armours in the previous two scenarios. It is not possible to identify from this diagram whether or not there is any benefit in using armour F or L rather than E or K. Nevertheless, it is still clear that protecting the thorax, then abdomen, then pelvis must be the priority.



Figures 9.13a & b: Lethal *UF and optimisation envelope for a No. 36 Mills grenade ($P_{occurrence}$ = 1)**

Figure 9.13b shows 2,865 optimum unbiased armour solutions. The maximum possible protection is estimated to save around 16 percent of lives that would otherwise be lost

($UF_{lethal} \approx 0.16$) in this scenario. If UF is subtracted from $P_{i,\ unarmoured}$ then maximum $P_{i,\ armoured}$ is found to be approximately 0.16. Hence, it is estimated that at least 16 percent of people would die in this scenario. This type of information helps the tactician or strategist decide whether or not their plans are viable and if armour has enough potential benefit.

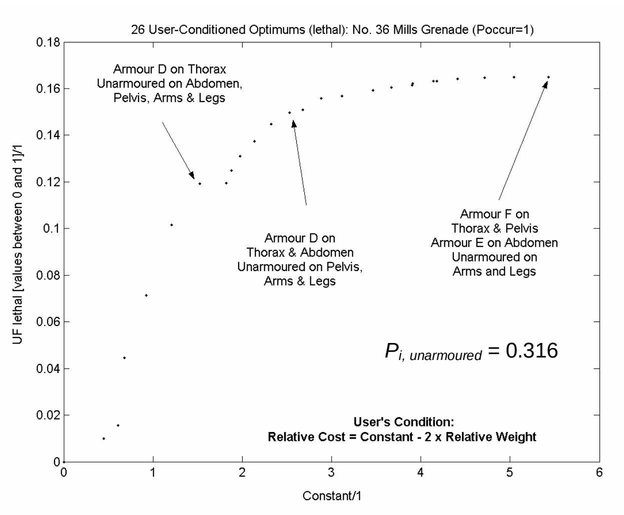
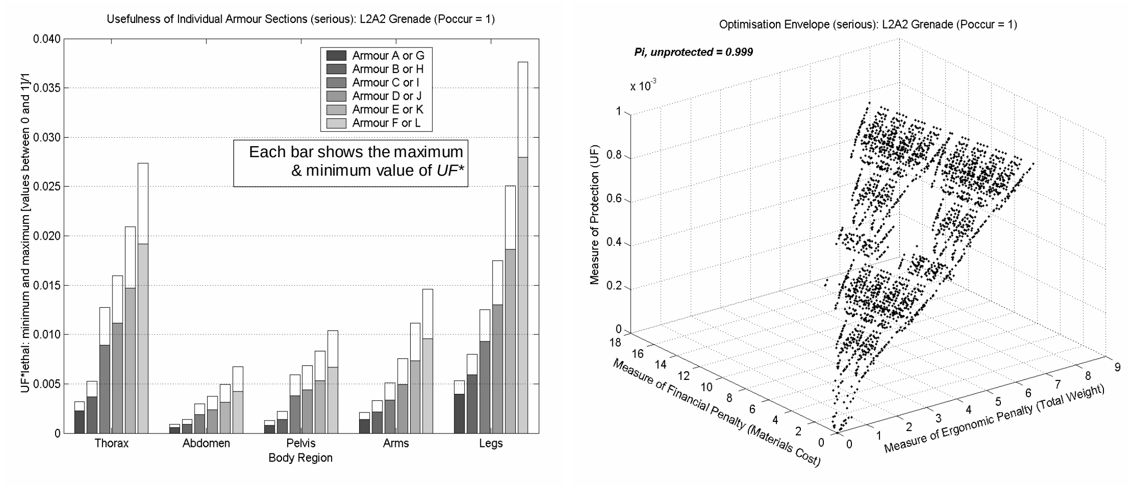


Figure 9.14: Lethal constrained optimisation envelope for a No. 36 Mills grenade ($P_{occurrence}$ = 1)

The 26 solutions in the user-constrained subset of optimums (Figure 9.14) limit the decision maker choice so that they are not overwhelmed by options. Of the three labelled solutions, the first looks particularly interesting because of the acute change in trend gradient. It shows that armour D on the thorax only offers three quarters of the maximum protection for a relatively small weight-cost penalty.

9.4.4 L2A2 grenade ($P_{occurrence}$ = 1), serious

Figures 9.15a and b show the effect of using the serious incapacitation criteria to assess the L2A2 scenario. The increased tolerances (compared to the lethal scenario) reflect the greater variety of protection possibilities on the rest of the body. *UF** becomes less helpful as the number of potential armour sections that can be combined increases. In Figure 9.15a for example, it is not possible to accurately distinguish between the benefits of wearing armours E or F (or K or L) on the thorax or E on the legs. Nevertheless, it is still possible to say that in general, for protection at the serious incapacitation level, it is better to armour the legs than the abdomen.



Figures 9.15a & b: Serious *UF and optimisation envelope for an L2A2 grenade ($P_{occurrence}$ = 1)**

The protection optimisation envelope demonstrates the inclusion of leg and arm injuries through the greater number of points (2,112). Moreover, the envelope does not have the sharp rise of the equivalent lethal scenario. Therefore, it is even more helpful if the user restricts the set of optimum solutions

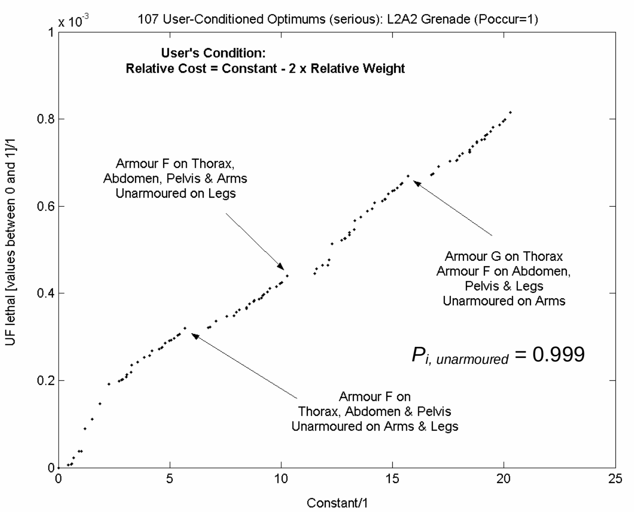
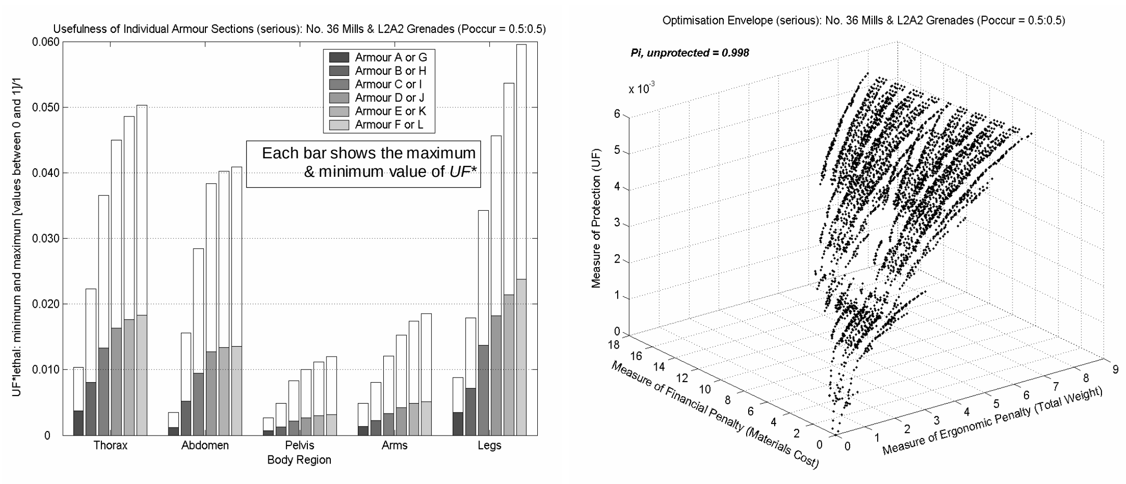


Figure 9.16: Serious constrained optimisation envelope for an L2A2 grenade ($P_{occurrence}$ = 1)

The constrained envelope (Figure 9.16) has 107 points of which three are immediately interesting. The first two show the benefit of wearing armour *a* (cheaper but slightly heavier than armour *b*) on the torso, abdomen, pelvis and legs. It is, perhaps, unsurprising that a single material is found to be useful over large portions of the body. However, the third point demonstrates that some optimum armours may be a combination of different materials as well as protection levels.

The high probability of being incapacitated (0.999 without armour) and the small degree of protection that can be afforded (*UF* < 0.01) reflects the danger of being 2m away from a grenade that is guaranteed to detonate. However, the scenarios are theoretical: $P_{occurrence}$ is likely to be much lower. The numerical values in this demonstration are not as important as the general trends.

9.4.5 36 Mills & L2A2 grenades ($P_{occurrence}$ = 0.5:0.5), serious



Figures 9.17a & b: Serious *UF and optimisation envelope for No. 36 Mills ($P_{occurrence}$ = 0.5) & L2A2 ($P_{occurrence}$ = 0.5) grenades**

The values of *UF** in Figure 9.17a can only be used to differentiate between the benefits of the three higher levels of armour on the thorax, abdomen and legs compared to the pelvis and arms. The optimisation envelope in Figure 9.17b is now much more useful than *UF** because all combinations of armour can be considered. 3,859 optimum solutions are found for this scenario. This is filtered down to 171 points with the stated user condition (see Figure 9.18).

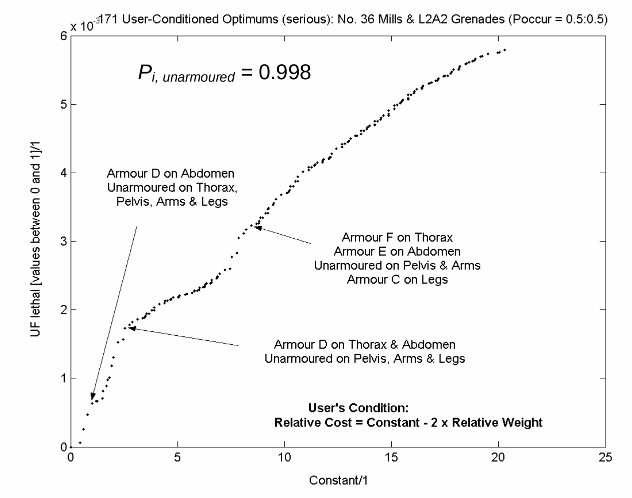
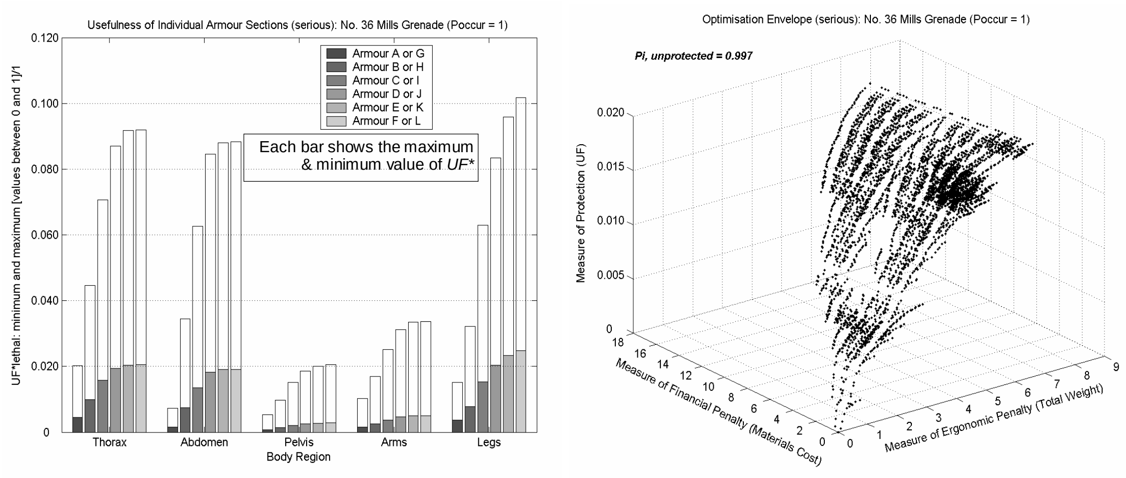


Figure 9.18: Serious constrained optimisation envelope for No. 36 Mills ($P_{occurrence}$ = 0.5) & L2A2 ($P_{occurrence}$ = 0.5) grenades

9.4.6 36 Mills grenade ($P_{occurrence}$ = 1), serious



Figures 9.19a & b: Serious *UF and optimisation envelope for a No. 36 Mills grenade ($P_{occurrence}$ = 1)**

Figure 9.19a show that it is no longer possible to get any useful information about the protection of the system – as a whole – from a graph of minimum and maximum values of *UF**. This is the result of a relatively wide variety of protection being available over the rest of the body.

Figure 9.19b presents 4,077 optimum points. The bifurcation of solutions is visible in the serious incapacitation scenarios. This is due to the choice of two materials of increasing thickness. It produces a hole in the centre of the envelope where no optimum solutions are possible.

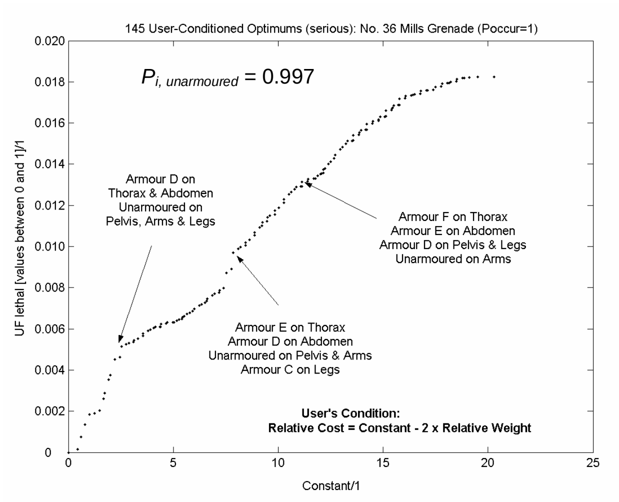


Figure 9.20: Serious constrained optimisation envelope for a No. 36 Mills grenade ($P_{occurrence}$ = 1)

The wide variety of possible solutions means that there is no clear distinction between the most useful sections of armour. The individual pieces must be considered as a system in order to reach a sensible design. In Figures 9.19b and 9.20, the armour design system outputs are presented in a clear format for the customer to use.

9.5 DISCUSSION

9.5.1 Pseudo-optimisation of protection using *UF**

*UF** on its own is not an optimisation tool; otherwise one would simply select the highest level of protection for all areas of the body. It must be traded off against ergonomic and financial penalties. However, the constraints need not be quantified. It is reasonable for the armour designer to liase with the customer and use their own judgement to deselect lesser solutions. Hence, *UF** is part of a 'quick and dirty' tool to enable designers to optimise protection. It is most helpful when there is little variation between the protection offered across the rest of the body. Thus, it is proposed that the use of *UF** should be limited to cases with few different armour sections, such as dividing the body into the three Kokinakis-Sperrazza lethal incapacitation regions.

9.5.2 The protection optimisation envelope

The protection optimisation envelope – in contrast with *UF** – is an optimisation tool. If the personal armour system continues to be refined as knowledge grows, it allows the designer to use simulation and automated optimisation to consider a greater number of options. Its weaknesses are twofold. Firstly, it is limited to models that can be quantified. Secondly, it is time-consuming to construct. Nevertheless, as models and computing continue to improve it is predicted that such quantitative methods will become more prevalent. For example, the authors have already used a different (quicker though less accurate) algorithm that reduces the optimisation time from around 20 computer-days to less than 2. This divides the constraints into a 90×90 mesh, where only the solution with highest value of *UF* is stored for each cell.

9.5.3 Adaptation of CASPER to synthesise personal armour design

Casualty reduction analysis tools are not sufficient on their own to synthesise personal armour design for optimisation: there are no constraints against which the benefits can be assessed. It has been demonstrated how CASPER can be modified to calculate the area of coverage, in order to find the total weight and material cost of each armour design: this is based on using the surface area of the person. It would be better to use the surface area of the armour instead. This requires further development of CASPER to attribute P_i to the armour rather than the area of the body.

9.6 CONCLUSIONS

1. The geometry files in casualty reduction analysis simulations such as CASPER can be modified to calculate the area of coverage for each section of armour. If the materials database is developed to include the areal density and cost per unit area, then the total weight and material cost of each armour design can be calculated automatically. This provides – albeit simplistic – constraints against which protection can be assessed. Hence, the foundations are laid for the world's first fully integrated personal armour design tools.

2. *UF** – the reduction in P_i due to wearing a given section of armour – is relatively quick and easy to produce. However, it is only helpful where the difference between maximum and minimum values is small relative to the mean value. This is proof that armour must be understood as part of a system.

3. A further limitation of *UF** is that it is only an estimate of protection. This must be traded-off against ergonomic and financial constraints, which are also dependent on the whole system. It is proposed that *UF** is one measure for 'quick and dirty' optimisation, especially if the constraint measures are qualitative.

4. A protection optimisation envelope – the maximum possible *UF* (usefulness of the whole armour system) for a given combination of ergonomic and financial constraints – can be used for quantitative materials selection. It removes undesirable solutions and provides the user, purchaser and operations analyst with the information necessary to select a particular armour design.

5. The disadvantage of using the protection optimisation envelope is that it is computationally expensive. Nevertheless, it is predicted that as more efficient optimisation algorithms are used, better ergonomic and financial models are produced and computer processor speeds increase this has potential to be an excellent method of selecting armour.

6. CASPER could be improved by including the probability of an event occurring ($P_{occurrence}$) in order to build up dynamic tasks and to study the effects of multiple threats. Moreover, the individual armour sections should be attributed with the value of P_i rather than the body regions.

9.7 RESEARCH RECOMMENDATIONS

It is proposed that more efficient optimisation algorithms are developed so that a protection optimisation envelope can be achieved in minutes rather than days. These could be built into a routine within CASPER.

CASPER could be adapted to attribute P_i to a particular segment of armour rather than a body region. It is already possible to distinguish between the benefit of a helmet and body armour.

Extension of this facility to individual armour segments makes CASPER a more powerful tool. It also makes it possible to use the armour geometry files to calculate the surface area of a garment rather than the person underneath.

Adding the probability of an event occurring, $P_{occurrence}$, to CASPER would make it possible to build up dynamic tasks and to study the effects of multiple threats automatically.

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CHAPTER 10: GENERAL CONCLUSIONS & RECOMMENDATIONS

10.1 INTRODUCTION

10.1.1 Aims

To summarise the major findings and recommendations of Chapters 5 to 9.

10.1.2 Objectives

- Present the key conclusions of this thesis in brief,
- Leave minor and detailed findings within the relevant chapters,
- Present the main research recommendations of this thesis.

10.1.3 Background

The quotation that defines this thesis is "As in life, so in a game of hazard, skill will make something of the worst of throws," (Falkner, 1898). Good armour design is a matter of making the best of a bad situation.

It is demonstrated in this thesis that it is possible to have too little or too much armour, in the wrong place and at the wrong time. The wise designer has an overarching understanding of the personal armour design system combined with specialist knowledge of relevant details. The successful designer has the methods and tools to trade off this knowledge to achieve the limits of possible solutions. The humble designer knows that this is where he or she should stop. It is up to the customer – be they wearer, commander or purchaser – to select the final solution: to take the ultimate risk.

This chapter is a summary of the knowledge found in this thesis in order to help the designer walk the paths to wisdom and success. Humility is perhaps best gained through respect of armour wearers who take the real risks and may one day pay the ultimate price.

10.2 ELICITATION OF PERSONAL ARMOUR DESIGN

10.2.1 Identification of an appropriate boundary

The system boundary used in this thesis is for the lifecycle of a single garment; for the combination of threat, environment, armour, wearer and task; and from the emergent properties to sub-subsystems such as materials properties. The commander and purchaser sit outside the system boundary and are the users of the capability that is enhanced or degraded by personal armour.

10.2.2 Definition of the designer's level of control

The designer has absolute control over the choice of materials, construction and coverage of armour to achieve the desired emergent properties. He or she has limited control of the way that armour is used.

10.2.3 Elicitation of the personal armour design system hierarchy

The pinnacle of the system hierarchy lies outside of the boundary. This is because it is the commander and or the purchaser who has the ultimate choice which personal armour design solution is acceptable. The system is then divided into three distinct but linked subsystems based around the main emergent properties.

10.2.4 Deduction of the key emergent properties

The system has three main emergent properties of protection, ergonomic effectiveness and financial cost effectiveness. The first is the positive benefit of armour; the second is the primary constraint; the third is a lesser constraint.

10.3 MEASUREMENT & MODELLING OF PROTECTION

10.3.1 Description of the protection subsystem

Protection can be understood as a five-stage model with two feedback loops. The stages imply that a threat must occur, hit a target, be resisted by armour and incapacitate the wearer. The difference in incapacitation between the armoured and unarmoured states is the protective benefit of armour. Feedback from making a task safer or the ergonomic penalty – such as making the wearer slower – affects protection by reducing or increasing respectively the likelihood of a threat occurring. Each stage and loop must be considered in order to account for the actual benefit of armour.

10.3.2 Identification of a suitable measure of protection effectiveness

The usefulness factor, *UF*, is the reduction in probability of incapacitation, P_i, with and without armour for a given incapacitation criterion. It is the best available quantitative measure of protection effectiveness because – in addition to accounting for the actual benefit of armour – it does not introduce bias from the designer. It is not up to him or her to dictate the relative weighting of death or classes of injury. Instead, values of *UF* for different incapacitation criteria should be supplied in order to help others such as wearers, commanders and medical doctors make qualitative trade-offs.

10.3.3 Demonstration of the novel use of CASPER to assess protection

Casualty reduction analysis tools such as CAPSER (Hunting Engineering, 1999) can be used to make tasks safer by minimising the probability of an unprotected casualty, $P_{c\ unprotected}$. This can be represented for an EOD operator as a map of P_i named the 'approach plot' allowing him to pick the safest route. It also enables accurate definition of minimum safe working distances.

'Zones of Usefulness' highlight the fact that close to a sufficiently large threat, amour is likely to be defeated so is of no use. A wearer is unlikely to be hit when far away from a threat and therefore armour is of no use. There may be a region in between where armour can be beneficial. Zones of Usefulness plots help a designer visualise which armour is likely to be useful for which location. They can also assist EOD operators to understand where it is worth donning/doffing a garment or using a shield. This should help to dispel the myth that an EOD suit only exists because "it enables you to be buried in one piece" (Dunstan, 1984).

10.3.4 Assessment of the Lightweight Combat EOD Suit

Modelling in Chapter 6 suggests that the Lightweight Combat EOD Suit is useful for personnel around unstable L2A2 and No. 36 Mills grenades, and BL755 sub-munitions. These emit large numbers of relatively small fragments, so the likelihood of being hit and protected is high. There is also a small zone of usefulness around the fuse of a 105mm shell lying on its side. However, the Lightweight Combat EOD Suit is not likely to be useful against a lone, upright HB876.

10.4 SECONDARY FRAGMENTATION FROM BURIED AP BLAST MINES

10.4.1 The probability of being hit, P_{hit}

The likelihood of being hit by secondary fragmentation from buried AP blast mines at a range of 1m decreases as an observer gets closer to ground level. Under the stated experimental conditions, P_{hit} is approximately 50 to 85% less next to the floor compared to directly above the mine. While the general result is unsurprising, the quantification in Chapter 7 gives further impetus for deminers to work in a prone position. Moreover, it provides a basis for threat assessment for unarmoured personnel.

10.4.2 The probability of a hit perforating armour, $P_{perforation|hit}$

No stones for the test threats are predicted to perforate current fragmentation armour. This conclusion is corroborated by the DLO DC R&PS (formerly DCTA) trials (Gotts, 1999) that were carried out in tandem with this work. This means that armour designers can ignore the multitude of secondary fragments from AP blast mines (for the given experimental conditions) if the wearer already has a garment with a V_0 of greater than approximately 200ms^{-1} for a 1.1g spherical steel fragment.

10.4.3 The probability of a hit incapacitating an unarmoured person, $P_{i|hit}$

Unprotected human skin at a range of 1m from a buried AP blast mine is likely to be penetrated by secondary fragments that hit it. A relatively low level of fragmentation resistance on a deminer’s hands, which are nearest to the mine, offers significant protection. This reinforces the rationale for fingerless gloves in the Lightweight Combat EOD Suit (Gotts, 2000).

10.4.4 Calibration of arena fragmentation trial impacts

The calibration method developed in Chapter 7 enables firing of single or multiple fragments of regular or irregular shapes and masses, up to the size constraints of the plastic wadding cup, for velocity ranges of 100-900ms^{-1}.

10.5 SUGGESTIONS FOR ERGONOMIC EFFECTIVENESS ASSESSMENT

10.5.1 The Mk 5 EOD Suit visor demister: an example of ergonomic design

Even simple models of the system can provide boundaries that minimise the degradation in ergonomic effectiveness. This point is demonstrated for the operation of a novel design of EOD visor demister; for which the maximum operating temperature of the inner visor surface is limited to the wearer's deep body temperature of approximately 39ºC. The power consumption is minimised by leaving a sealed air gap between the visor and demister; and by using temperature regulation. This minimises the rate of heat storage and weight carried by the wearer due to using the device to prevent system failure by visor misting.

10.5.2 Measurement of ergonomic effectiveness

Ergonomic effectiveness is measured in three stages: materials assessment, garment testing without the wearer and garment testing with the wearer. The designer must alert any decision maker to the system level at which armour is assessed; and include sufficient depth in the system context for measures to be useful.

Measures of effectiveness should be used to compare personal armour designs rather than measures of performance because the former are comparisons of the armoured and unarmoured states.

10.5.3 Potential future assessment of ergonomic effectiveness

Currently, the best way to assess ergonomic effectiveness is through wearer trials; however this requires the construction of real prototypes and the availability of suitable test subjects. Simulation of the ergonomics of armour could be used to make predictions in the same way as CASPER is employed to assess protection. Computational biomechanical models have the potential to be reversed in order to calculate the muscular burden due to wearing armour. A novel extension is to use muscle efficiencies to produce a biothermodynamical model. These tools could be used to predict the change in ergonomic effectiveness for three of the major degradation mechanisms – muscle fatigue, reduced reach and overheating.

10.6 SYNTHESIS & OPTIMISATION OF PERSONAL ARMOUR DESIGN

10.6.1 Development of optimisation methods: *UF**

*UF** – the reduction in P_i due to wearing a given section of armour – is a 'quick and dirty' tool for estimating the protective contribution of the section. This can be used to trade off protection with constraints of armour that are difficult to quantify. However, it is only applicable when the difference between maximum and minimum values of *UF** are small relative to the mean value. This is proof that armour must be understood as part of a system.

10.6.2 Development of optimisation methods: protection optimisation envelope

A protection optimisation envelope – the maximum possible *UF* (usefulness of the whole armour system) for a given combination of ergonomic and financial constraints – can be used for quantitative materials selection. It removes undesirable solutions and provides the user, purchaser and operations analyst with the information necessary to select a particular armour design.

10.6.3 Demonstration of the novel adaptation of CASPER to optimise personal armour

The geometry files in casualty reduction analysis simulations such as CASPER can be modified to calculate the area of coverage for each section of armour. If the materials database is developed to include the areal density and cost per unit area, then the total weight and material cost of each armour design can be calculated automatically. This provides constraints for the formation of a protection optimisation envelope. Hence, the foundations are laid for the world's first fully integrated personal armour design tools.

10.7 RESEARCH RECOMMENDATIONS

10.7.1 Refine the system model

It is recommended that the system model of Chapter 5 is refined and developed to reflect the growth in knowledge of personal armour design. The goal is not only to look at a wider, deeper, longer system boundary but also to join up the constituent components more rigorously. For example, formal descriptions of different incapacitation mechanisms need to be linked together more thoroughly – perhaps by predicting the probability of incapacitation for different grades of a trauma score. Moreover, the synergistic effects of multiple injuries need further research. The same is true for the multitude of ergonomic degradation mechanisms that could be linked together more completely. The subsystems then need to be joined together in greater detail to evaluate the links between them.

10.7.2 Improve CASPER

It is recommended that CASPER is developed in the following ways.

1. Include all injury mechanisms, e.g. the three stages of blast incapacitation. A simpler option would be to generate minimum range data – below which CASPER data is no longer acceptable without being combined with blast trials – as demonstrated in Section 6.5.8.

2. Build in a function to combine threats using the probability of occurrence. This would make the estimation of protection for dynamic tasks and multiple threats simpler.

3. Attribute P_i to armour sections as well as body sections. This is already carried out for the helmet and other armour. If this is done, then the benefit of individual sections of armour can be estimated in a single run.

4. Build in a function to calculate the area of armour as approximated in Section 9.3.3. This can be combined with areal density and cost per unit area data – that can be stored in the materials database – to automatically generate weight and materials cost figures for armour designs.

5. Develop efficient optimisation routines to generate protection optimisation envelopes as demonstrated in Chapter 9. This means that an armour designer could set CASPER running overnight to test multiple parameters and review the best possible options in the morning.

6. Use the CASPER man's geometry to estimate his centre of mass. If areal density properties are added to the armour model, this would enable the designer to examine factors such as the effect on wearer balance.

10.7.3 Support the development of ergonomics simulation

Biomechanical and biothermodynamical simulations are on the verge of becoming a sensible option for designers. Further research should be conducted to (i) build models of armour into and (ii) verify the use of muscular efficiency in PAM-Comfort™, as proposed in Chapter 8. This will require a longer period of research than the developments for CASPER suggested in Sections 10.7.2 and 10.7.4.

10.7.4 Link CASPER and CAEn

Casualty reduction analysis software (e.g. CASPER) can provide incapacitation data as a lookup table in operational analysis (OA) programs such as the UK MOD's Close Action Environment (CAEn). The OA tools then give scenarios to examine with casualty reduction analysis. The two types of programs operate at separate levels of fidelity: CASPER focuses on a static man with a single threat; while CAEn is a dynamic section-level (small group of people) simulation. This means that it is difficult to transfer data between one program and the other. It is recommended that the interface between the two programs is improved in order to facilitate both OA and personal armour design.

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APPENDIX A: ANALYSIS OF THE EFFECTS OF SECONDARY FRAGMENTATION FROM BURIED AP BLAST MINES

A.1 STONE PROPERTIES

	Small Stones mass, *m* / g	**Large Stones mass, *m* / g**
	0.57	2.34
	0.42	3.21
	0.28	0.95
	0.74	1.56
	0.79	5.15
	0.52	2.18
	0.27	1.02
	0.79	3.94
	0.59	1.76
	0.80	2.39
	0.63	1.54
	0.62	2.96
	0.49	1.39
	0.53	1.56
	0.47	8.96
	0.66	6.73
	1.46	8.12
	0.55	2.11
	0.50	7.75
	0.54	4.69
	0.94	2.38
	0.51	9.57
	0.75	4.50
	0.53	10.45
	0.45	6.13
	0.35	4.53
	0.49	5.36
	0.98	5.21
	0.65	3.54
	0.38	2.29
Total Mass	18.25	124.27
Mean Mass	0.61	4.14
Standard Deviation	0.24	2.71

Table A1: Stone grades

	Reading 1	**Reading 2**
Stone Grades / 1	Small & Large	Small & Large
Dry Mass / g	104.5	100.3
Wet volume (after soaking overnight) / ml	52	42
Mean Density, ρ / kgm^{-3}	2010	2388

Table A2: Approximate stone densities

A.2 SPHERICAL COORDINATES† & INCIDENCE ANGLES‡

Pack	Rectangle	Charge Depth = 5cm Radius, r /cm	Theta, ϑ / °	Phi, ϕ / °	Incidence, β / °	Charge Depth = 10cm Radius, r /cm	Theta, ϑ / °	Phi, ϕ / °	Incidence, β / °
A	1	102	39	24	32	107	37	24	33
	2	99	36	0	26	103	35	0	27
	3	102	39	336	32	107	37	336	33
	4	94	58	19	19	97	55	19	20
	5	90	56	0	6	93	54	0	8
	6	94	58	341	19	97	55	341	20
	7	96	78	16	22	98	75	16	20
	8	93	78	0	16	94	75	0	13
	9	96	78	344	22	98	75	344	20
B	1	96	34	119	38	101	32	119	39
	2	93	30	90	32	97	29	90	33
	3	96	34	61	38	101	32	61	39
	4	85	54	112	23	88	51	112	24
	5	80	52	90	10	84	49	90	13
	6	85	54	68	23	88	51	68	24
	7	86	76	108	22	86	73	108	21
	8	81	76	90	14	83	72	90	10
	9	86	76	72	22	86	73	72	21
C	1	102	39	204	32	107	37	204	33
	2	99	36	180	26	103	35	180	27
	3	102	39	156	32	107	37	156	33
	4	94	58	199	19	97	55	199	20
	5	90	56	180	6	93	54	180	8
	6	94	58	161	19	97	55	161	20
	7	96	78	196	22	98	75	196	20
	8	93	78	180	16	94	75	180	13
	9	96	78	164	22	98	75	164	20
D	1	96	34	299	38	101	32	299	39
	2	93	30	270	32	97	29	270	33
	3	96	34	241	38	101	32	241	39
	4	85	54	292	23	88	51	292	24
	5	80	52	270	10	84	49	270	13
	6	85	54	248	23	88	51	248	24
	7	86	76	288	22	86	73	288	21
	8	81	76	270	14	83	72	270	10
	9	86	76	252	22	86	73	252	21
E	1	104	24	323	24	109	23	323	23
	2	101	20	0	20	106	19	0	19
	3	104	24	37	24	109	23	37	23
	4	98	15	270	15	103	15	270	15
	5	95	0	0	0	100	0	0	0
	6	98	15	90	15	103	15	90	15
	7	104	24	217	24	109	23	217	23
	8	101	20	180	20	106	19	180	19
	9	104	24	143	24	109	23	143	23

Table A3: Spherical coordinates & incidence angles

† Radius, r is measured from the charge top-centre to the centre of each layer 1 rectangle;
Theta, ϑ is measured from the vertical (normal to the ground plane);
Phi, ϕ is measured clockwise, looking up at the target panels from the charge.

‡ Incidence angle, β is defined as the angle between the radius and the panel normal. It is calculated from the spherical coordinates.

A.3 CALIBRATION RAW DATA

Shot Number / 1	**Mass, *m* / g**	**Strike Velocity, V_s / ms^{-1}**	**Maximum Depth *d* / layers**	**Maximum Depth *d* / mm**
1	1.226	252	1	3.75
2	0.668	132	1	3.75
3	0.536	297	2	7.5
4	0.227	293	1	3.75
5	0.818	391	3	11.25
6	0.497	368	2	7.5
7	0.282	240	1	3.75
8	0.323	449	3	11.25
9	0.406	495	3	11.25
10	1.99	343	4	15
11	2.789	365	6	22.5
12	3.68	421	5	18.75
13	3.974	431	10	37.5
14	2.039	406	7	26.25
15	3.287	490	7	26.25
16	1.358	477	7	26.25
17	1.19	440	5	18.75
18	3.642	530	9	33.75
19	1.35	327	4	15
20	0.663	337	3	11.25
21	0.875	287	3	11.25
22	0.492	393	2	7.5
23	0.218	351	1	3.75
24	0.694	424	4	15
25	0.511	414	3	11.25
26	0.488	471	3	11.25
27	0.485	509	3	11.25
28	3.671	371	7	26.25
29	2.406	373	5	18.75
30	2.536	361	5	18.75
31	1.177	442	4	15
32	1.619	425	4	15
33	2.298	452	5	18.75
34	4.329	551	8	8
35	2.091	521	5	18.75
36	2.396	589	7	26.25
37	2.226	623	9	33.75
38	0.217	356	1	3.75
39	0.547	616	5	18.75
40	0.339	558	3	11.25
41	0.388	378	1	3.75
42	0.724	666	5	18.75
43	0.945	752	6	22.5
44	0.262	543	2	7.5
45	0.529	744	6	22.5
46	2.056	593	7	26.25
47	2.436	616	5	18.75
48	2.709	727	11	41.25
49	1.646	641	6	22.5
50	1.651	654	7	26.25

----- shots 51to 63 listed on next page -----

Shot Number / 1	**Mass, *m* / g**	**Strike Velocity, V_s / ms^{-1}**	**Maximum Depth *d* / layers**	**Maximum Depth *d* / mm**
51	2.026	639	9	33.75
52	1.823	714	7	26.25
53	1.678	752	9	33.75
54	1.467	726	8	30
55	1.968	733	5	18.75
56	0.603	327	4	15
57	0.637	693	3	11.25
58	0.413	559	2	7.5
59	0.553	712	3	11.25
60	0.284	775	4	15
61	0.843	765	7	26.25
62	1.367	854	10	37.5
63	2.031	852	9	33.75

Table A4: Calibration raw data

A.4 CALIBRATION DATA TRANSFORMATION (MATLAB® M-FILE)

```
%-----------------------------------------------------------------
%Written originally by Dr T Ringrose, Cranfield University.
%Adapted by C Couldrick, Cranfield University.
%Filename is cal.m
%Regression analysis of calibration raw data with 95%tolerance
%limits.

%Load calibration raw data.
      load calfragdata;
      calfrag(:,1:4) = calfragdata(:,2:5);

%Mass, strike velocity and depth of maximum penetration or
%witness mark in mm for each calibration shot.
      m = calfrag(:,1);
      v = calfrag(:,2);
      d = calfrag(:,4);

%y values using 3 different models.
      momdens = m.^(1/3).*v;
      log_ked = m.^(1/3).*v.*v;
      log_ks = log(m.*v.^(3/2));

%Depth values in mm for layers 1 to 11.
      dvals = (3.75:3.75:41.25)';

%Experimental datum points. ‘momdens’ is changed to ‘log_ked’ or
%‘log_ks’ depending on the model of interest.
      y = log_ks;
      x = d;

%1 + the order of the regression equation: p=2 for linear
%(i.e. momdens); p=3 for quadratic (i.e. log_ked or log_ks).
      p = 3;

      n = size(calfrag,1);

%Standard regression. The required output is ti95, which %presents the
estimated conditional mean with tolerance limits %for the model type,
e.g. momentum density, etc.
      X = ones(size(calfrag,1),p);
      X(:,2) = x;
      X(:,3) = x.^2;
      betahat = (X'*X)\X'*y;
      yhat = X*betahat;
      rss = (y-yhat)'*(y-yhat);
      rms = rss/(n-p);
      covbetahat = inv(X'*X)*rms;
      x0 = ones(size(dvals,1),p);
      x0(:,2) = dvals;
      x0(:,3) = dvals.^2;
      sds = sqrt(diag(x0*covbetahat*x0'));
      sdti = sqrt(rms+sds.^2);
      tcrit = tinv(0.975,n-p);
      y0hat = x0*betahat;
      ci95 = zeros( size(dvals,1), 3 );
      ci95(:,1) = y0hat-tcrit.*sds;
      ci95(:,2) = y0hat;
```

```
      ci95(:,3) = y0hat+tcrit.*sds;
      ti95 = zeros( size(dvals,1), 3 );
      ti95(:,1) = y0hat-tcrit.*sdti;
      ti95(:,2) = y0hat;
      ti95(:,3) = y0hat+tcrit.*sdti;
%-----------------------------------------------------------------
```

A.5 CALIBRATION RESULTS

d / layers	d / mm	$m^{1/3}V_s$ / $g^{1/3}ms^{-1}$ lower 95% tolerance	estimated mean	upper 95% tolerance.	$\log_e(m^{1/3}V_s^2$ / $g^{1/3}m^2s^{-2})$ lower 95% tolerance	estimated mean	upper 95% tolerance	$\log_e(mV_s^{3/2}$ / $gm^{3/2}s^{-3/2})$ lower 95% tolerance	estimated mean	upper 95% tolerance
1	3.75	-1.6	231.1	463.8	10.1	11.1	12.1	6.5	7.4	8.3
2	7.5	80.2	311.1	542.1	10.6	11.5	12.5	7.2	8.1	9.0
3	11.25	161.4	391.2	620.9	11.0	11.9	12.9	7.8	8.7	9.5
4	15	242.2	471.2	700.2	11.3	12.3	13.2	8.3	9.2	10.0
5	18.75	322.5	551.3	780.1	11.6	12.6	13.5	8.7	9.6	10.5
6	22.5	402.2	631.3	860.5	11.8	12.8	13.8	9.1	10.0	10.8
7	26.25	481.4	711.4	941.4	12.0	13.0	14.0	9.4	10.2	11.1
8	30	560.1	791.4	1022.8	12.2	13.1	14.1	9.6	10.4	11.3
9	33.75	638.3	871.5	1104.7	12.2	13.2	14.2	9.7	10.6	11.5
10	37.5	716.0	951.5	1187.1	12.2	13.2	14.3	9.7	10.6	11.5
11	41.25	793.2	1031.6	1270.0	12.1	13.2	14.3	9.6	10.6	11.6

Table A5: Calibration results

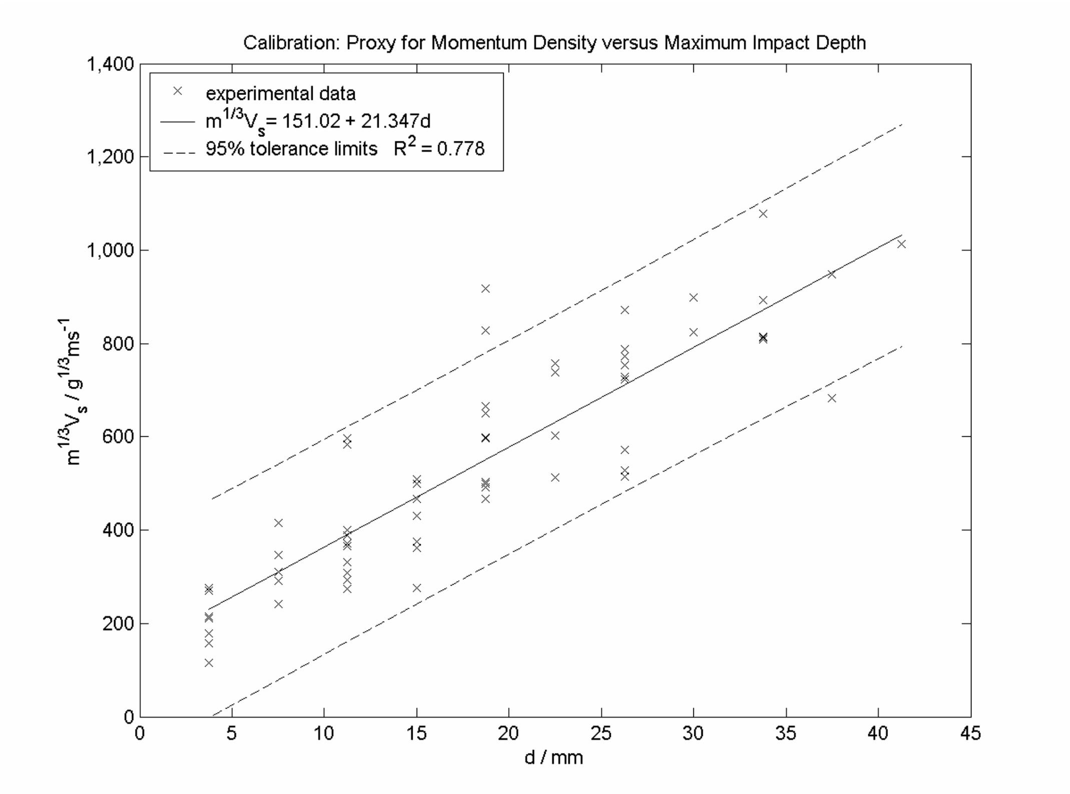


Figure A1: Calibration curve for a proxy for momentum density

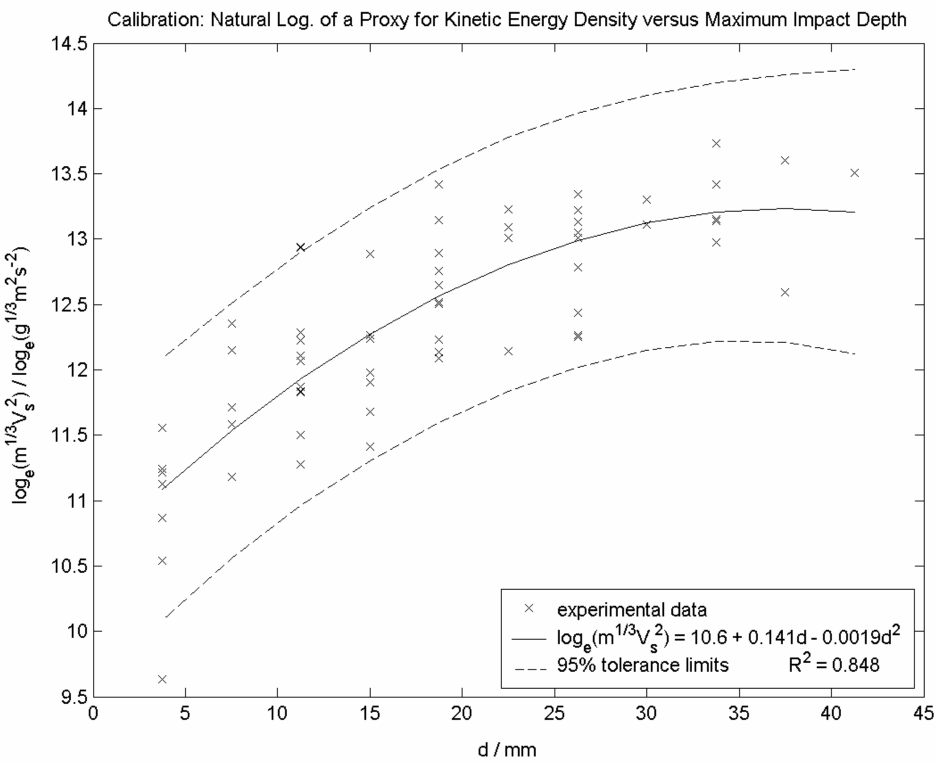


Figure A2: Calibration curve for a proxy for kinetic energy density

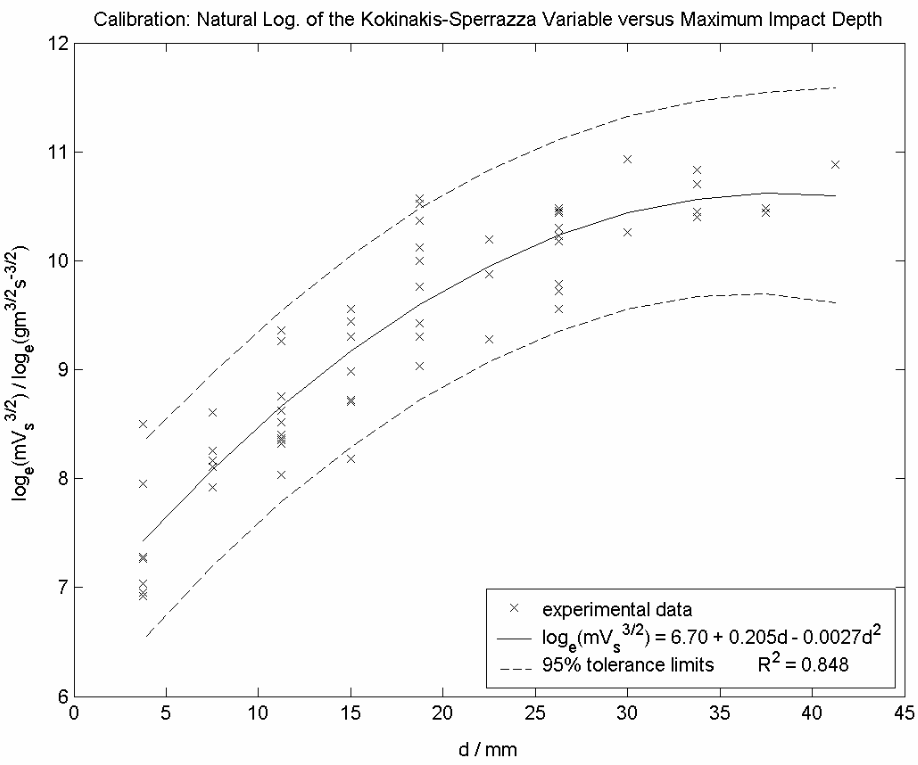


Figure A3: Calibration curve for the Kokinakis-Sperrazza variable

A.6 TRIALS RAW DATA

Pack / 1	Rectangle / 1	Angle / º	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	37	0	0	0	0	0	0	0	0	0	0	0
	2	35	1	0	0	0	0	0	0	0	0	0	1
	3	37	0	0	0	0	0	0	0	0	0	0	0
	4	55	0	0	0	0	0	0	0	0	0	0	0
	5	54	0	0	0	0	0	0	0	0	0	0	0
	6	55	0	0	0	0	0	0	0	0	0	0	0
	7	75	0	0	0	0	0	0	0	0	0	0	0
	8	75	2	0	0	0	0	0	0	0	0	0	2
	9	75	0	0	0	0	0	0	0	0	0	0	0
B	1	32	0	0	0	0	0	0	0	0	0	0	0
	2	29	1	0	0	0	0	0	0	0	0	0	1
	3	32	0	0	0	0	0	0	0	0	0	0	0
	4	51	0	0	0	0	0	0	0	0	0	0	0
	5	49	0	0	0	0	0	0	0	0	0	0	0
	6	51	0	0	0	0	0	0	0	0	0	0	0
	7	73	0	0	0	0	0	0	0	0	0	0	0
	8	72	0	0	0	0	0	0	0	0	0	0	0
	9	73	0	0	0	0	0	0	0	0	0	0	0
C	1	37	0	0	0	0	0	0	0	0	0	0	0
	2	35	0	0	0	0	0	0	0	0	0	0	0
	3	37	0	0	0	0	0	0	0	0	0	0	0
	4	55	0	0	0	0	0	0	0	0	0	0	0
	5	54	0	0	0	0	0	0	0	0	0	0	0
	6	55	0	0	0	0	0	0	0	0	0	0	0
	7	75	0	0	0	0	0	0	0	0	0	0	0
	8	75	0	0	0	0	0	0	0	0	0	0	0
	9	75	0	0	0	0	0	0	0	0	0	0	0
D	1	32	0	0	0	0	0	0	0	0	0	0	0
	2	29	1	0	0	0	0	0	0	0	0	0	1
	3	32	0	0	0	0	0	0	0	0	0	0	0
	4	51	0	0	0	0	0	0	0	0	0	0	0
	5	49	0	0	0	0	0	0	0	0	0	0	0
	6	51	1	0	0	0	0	0	0	0	0	0	1
	7	73	0	0	0	0	0	0	0	0	0	0	0
	8	72	0	0	0	0	0	0	0	0	0	0	0
	9	73	0	0	0	0	0	0	0	0	0	0	0
E	1	23	3	0	0	0	0	0	0	0	0	0	3
	2	19	4	2	0	0	0	0	0	0	0	0	6
	3	23	0	0	0	0	0	0	0	0	0	0	0
	4	15	4	0	0	3	0	0	0	0	0	0	7
	5	0	10	0	0	5	1	0	0	0	0	0	16
	6	15	4	0	0	0	0	0	0	0	0	0	4
	7	23	2	0	0	0	0	0	0	0	0	0	2
	8	19	2	1	0	1	0	0	0	0	0	0	4
	9	23	1	0	0	0	0	0	0	0	0	0	1

Table A6: Trial 1: 50g PE4, 10cm depth, small stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	18	0	0	0	0	0	0	0	0	0	18
	2	36	20	0	0	0	0	0	0	0	0	0	20
	3	39	18	1	0	0	0	0	0	0	0	0	19
	4	58	4	0	0	0	0	0	0	0	0	0	4
	5	56	10	1	0	0	0	0	0	0	0	0	11
	6	58	14	0	0	0	0	0	0	0	0	0	14
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
B	1	34	30	3	1	0	0	0	0	0	0	0	34
	2	30	20	2	1	0	0	0	0	0	0	0	23
	3	34	17	0	0	0	0	0	0	0	0	0	17
	4	54	16	0	0	0	0	0	0	0	0	0	16
	5	52	11	0	0	0	0	0	0	0	0	0	11
	6	54	7	0	0	0	0	0	0	0	0	0	7
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
C	1	39	6	0	0	0	0	0	0	0	0	0	6
	2	36	7	0	0	0	0	0	0	0	0	0	7
	3	39	0	0	0	0	0	0	0	0	0	0	0
	4	58	3	0	0	0	0	0	0	0	0	0	3
	5	56	3	0	0	0	0	0	0	0	0	0	3
	6	58	1	0	0	0	0	0	0	0	0	0	1
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
D	1	34	4	0	0	0	0	0	0	0	0	0	4
	2	30	10	0	0	0	0	0	0	0	0	0	10
	3	34	9	0	0	0	0	0	0	0	0	0	9
	4	54	3	0	0	0	0	0	0	0	0	0	3
	5	52	23	1	0	0	0	0	0	0	0	0	24
	6	54	12	0	0	0	0	0	0	0	0	0	12
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	1	0	0	0	0	0	0	0	0	0	1
E	1	24	74	19	4	0	0	0	0	0	0	0	97
	2	20	55	18	5	0	0	0	0	0	0	0	78
	3	24	36	12	2	0	0	0	0	0	0	0	50
	4	15	118	51	15	3	0	0	0	0	0	0	187
	5	0	159	43	8	5	1	0	0	0	0	0	216
	6	15	94	28	7	0	0	0	0	0	0	0	129
	7	24	32	3	0	0	0	0	0	0	0	0	35
	8	20	45	10	1	1	0	0	0	0	0	0	57
	9	24	36	10	1	0	0	0	0	0	0	0	47

Table A7: Trial 2: 100g PE4, 5cm depth, small stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	30	6	0	0	0	0	0	0	0	0	36
	2	36	26	5	0	0	0	0	0	0	0	0	31
	3	39	11	0	0	0	0	0	0	0	0	0	11
	4	58	19	1	0	0	0	0	0	0	0	0	20
	5	56	54	4	0	0	0	0	0	0	0	0	58
	6	58	42	1	0	0	0	0	0	0	0	0	43
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	1	0	0	0	0	0	0	0	0	0	1
	9	78	1	0	0	0	0	0	0	0	0	0	1
B	1	34	25	1	0	0	0	0	0	0	0	0	26
	2	30	45	3	1	0	0	0	0	0	0	0	49
	3	34	50	3	0	0	0	0	0	0	0	0	53
	4	54	9	0	0	0	0	0	0	0	0	0	9
	5	52	28	1	0	0	0	0	0	0	0	0	29
	6	54	11	0	0	0	0	0	0	0	0	0	11
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
C	1	39	7	0	0	0	0	0	0	0	0	0	7
	2	36	10	0	0	0	0	0	0	0	0	0	10
	3	39	15	1	0	0	0	0	0	0	0	0	16
	4	58	3	0	0	0	0	0	0	0	0	0	3
	5	56	9	1	0	0	0	0	0	0	0	0	10
	6	58	4	1	0	0	0	0	0	0	0	0	5
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
D	1	34	13	0	0	0	0	0	0	0	0	0	13
	2	30	30	1	0	0	0	0	0	0	0	0	31
	3	34	23	0	0	0	0	0	0	0	0	0	23
	4	54	2	0	0	0	0	0	0	0	0	0	2
	5	52	8	0	0	0	0	0	0	0	0	0	8
	6	54	9	1	0	0	0	0	0	0	0	0	10
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
E	1	24	104	28	3	0	0	0	0	0	0	0	135
	2	20	119	37	15	2	0	0	0	0	0	0	173
	3	24	75	27	5	1	0	0	0	0	0	0	108
	4	15	124	36	8	0	0	0	0	0	0	0	168
	5	0	198	82	28	5	0	0	0	0	0	0	313
	6	15	112	41	12	3	1	0	0	0	0	0	169
	7	24	79	14	0	0	0	0	0	0	0	0	93
	8	20	73	18	1	0	0	0	0	0	0	0	92
	9	24	96	24	5	1	0	0	0	0	0	0	126

Table A8: Trial 3: 200g PE4, 5cm depth, small stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	69	24	2	0	0	0	0	0	0	0	95
	2	36	86	27	4	1	0	0	0	0	0	0	118
	3	39	65	11	2	0	0	0	0	0	0	0	78
	4	58	128	31	4	1	0	0	0	0	0	0	164
	5	56	137	44	11	3	1	0	0	0	0	0	196
	6	58	103	18	5	0	0	0	0	0	0	0	126
	7	78	8	1	0	0	0	0	0	0	0	0	9
	8	78	34	6	0	0	0	0	0	0	0	0	40
	9	78	1	1	0	0	0	0	0	0	0	0	2
B	1	34	104	26	3	0	0	0	0	0	0	0	133
	2	30	96	23	1	1	0	0	0	0	0	0	121
	3	34	38	1	0	0	0	0	0	0	0	0	39
	4	54	39	3	0	0	0	0	0	0	0	0	42
	5	52	33	1	0	0	0	0	0	0	0	0	34
	6	54	7	0	0	0	0	0	0	0	0	0	7
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
C	1	39	31	1	0	0	0	0	0	0	0	0	32
	2	36	67	5	0	0	0	0	0	0	0	0	72
	3	39	55	4	1	0	0	0	0	0	0	0	60
	4	58	8	0	0	0	0	0	0	0	0	0	8
	5	56	26	0	0	0	0	0	0	0	0	0	26
	6	58	19	0	0	0	0	0	0	0	0	0	19
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
D	1	34	21	2	1	0	0	0	0	0	0	0	24
	2	30	8	0	0	0	0	0	0	0	0	0	8
	3	34	24	2	1	0	0	0	0	0	0	0	27
	4	54	36	0	0	0	0	0	0	0	0	0	36
	5	52	20	0	0	0	0	0	0	0	0	0	20
	6	54	11	0	0	0	0	0	0	0	0	0	11
	7	76	1	0	0	0	0	0	0	0	0	0	1
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
E	1	24	259	85	35	19	2	2	0	0	0	0	402
	2	20	156	106	51	16	6	1	1	0	0	0	337
	3	24	215	53	22	7	3	0	0	0	0	0	300
	4	15	256	103	43	11	1	0	0	0	0	0	414
	5	0	355	158	72	33	8	1	1	0	0	0	628
	6	15	197	48	20	6	3	0	0	0	0	0	274
	7	24	130	37	9	1	0	0	0	0	0	0	177
	8	20	116	34	7	0	0	0	0	0	0	0	157
	9	24	112	25	6	1	0	0	0	0	0	0	144

Table A9: Trial 4: 500g PE4, 5cm depth, small stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	13	1	0	0	0	0	0	0	0	0	14
	2	36	17	2	1	0	0	0	0	0	0	0	20
	3	39	5	1	0	0	0	0	0	0	0	0	6
	4	58	4	0	0	0	0	0	0	0	0	0	4
	5	56	9	0	0	0	0	0	0	0	0	0	9
	6	58	7	0	0	0	0	0	0	0	0	0	7
	7	78	1	0	0	0	0	0	0	0	0	0	1
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
B	1	34	5	0	0	0	0	0	0	0	0	0	5
	2	30	9	1	1	0	0	0	0	0	0	0	11
	3	34	4	0	0	0	0	0	0	0	0	0	4
	4	54	6	0	0	0	0	0	0	0	0	0	6
	5	52	3	0	0	0	0	0	0	0	0	0	3
	6	54	7	2	0	0	0	0	0	0	0	0	9
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
C	1	39	9	0	0	0	0	0	0	0	0	0	9
	2	36	16	1	0	0	0	0	0	0	0	0	17
	3	39	20	2	0	0	0	0	0	0	0	0	22
	4	58	4	2	0	0	0	0	0	0	0	0	6
	5	56	10	1	1	0	0	0	0	0	0	0	12
	6	58	2	0	0	0	0	0	0	0	0	0	2
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
D	1	34	12	0	0	0	0	0	0	0	0	0	12
	2	30	9	1	1	0	0	0	0	0	0	0	11
	3	34	12	0	0	0	0	0	0	0	0	0	12
	4	54	12	0	0	0	0	0	0	0	0	0	12
	5	52	7	0	0	0	0	0	0	0	0	0	7
	6	54	12	2	0	0	0	0	0	0	0	0	14
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
E	1	24	30	8	3	1	0	0	0	0	0	0	42
	2	20	21	5	1	0	0	0	0	0	0	0	27
	3	24	33	7	2	0	0	0	0	0	0	0	42
	4	15	31	5	2	0	0	0	0	0	0	0	38
	5	0	58	12	2	1	0	0	0	0	0	0	73
	6	15	39	14	5	0	0	0	0	0	0	0	58
	7	24	25	5	0	0	0	0	0	0	0	0	30
	8	20	33	6	3	1	1	0	0	0	0	0	44
	9	24	22	5	2	0	0	0	0	0	0	0	29

Table A10: Trial 5: 50g PE4, 5cm depth, large stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	11	2	0	0	0	0	0	0	0	0	13
	2	36	14	0	0	0	0	0	0	0	0	0	14
	3	39	8	0	0	0	0	0	0	0	0	0	8
	4	58	13	2	0	0	0	0	0	0	0	0	15
	5	56	14	0	0	0	0	0	0	0	0	0	14
	6	58	2	0	0	0	0	0	0	0	0	0	2
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
B	1	34	14	2	2	0	0	0	0	0	0	0	18
	2	30	31	3	1	1	0	0	0	0	0	0	36
	3	34	19	4	0	0	0	0	0	0	0	0	23
	4	54	3	1	0	0	0	0	0	0	0	0	4
	5	52	5	2	1	0	0	0	0	0	0	0	8
	6	54	4	0	0	0	0	0	0	0	0	0	4
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	0	0	0	0	0	0	0	0	0	0	0
	9	76	0	0	0	0	0	0	0	0	0	0	0
C	1	39	7	0	0	0	0	0	0	0	0	0	7
	2	36	11	1	0	0	0	0	0	0	0	0	12
	3	39	6	0	0	0	0	0	0	0	0	0	6
	4	58	11	2	0	0	0	0	0	0	0	0	13
	5	56	8	2	1	0	0	0	0	0	0	0	11
	6	58	4	0	0	0	0	0	0	0	0	0	4
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	1	0	0	0	0	0	0	0	0	0	1
	9	78	1	0	0	0	0	0	0	0	0	0	1
D	1	34	15	0	0	0	0	0	0	0	0	0	15
	2	30	7	0	0	0	0	0	0	0	0	0	7
	3	34	3	2	0	0	0	0	0	0	0	0	5
	4	54	7	0	0	0	0	0	0	0	0	0	7
	5	52	12	1	0	0	0	0	0	0	0	0	13
	6	54	4	0	0	0	0	0	0	0	0	0	4
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	1	0	0	0	0	0	0	0	0	0	1
	9	76	0	0	0	0	0	0	0	0	0	0	0
E	1	24	9	1	0	0	0	0	0	0	0	0	10
	2	20	14	1	0	0	0	0	0	0	0	0	15
	3	24	15	5	2	2	0	0	0	0	0	0	24
	4	15	7	0	0	0	0	0	0	0	0	0	7
	5	0	40	7	2	1	0	0	0	0	0	0	50
	6	15	21	4	2	0	0	0	0	0	0	0	27
	7	24	4	0	0	0	0	0	0	0	0	0	4
	8	20	8	2	1	0	0	0	0	0	0	0	11
	9	24	29	4	3	1	0	0	0	0	0	0	37

Table A11: Trial 6: 100g PE4, 5cm depth, large stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	23	11	4	0	0	0	0	0	0	0	38
	2	36	35	8	3	1	0	0	0	0	0	0	47
	3	39	37	6	2	0	0	0	0	0	0	0	45
	4	58	35	10	1	0	0	0	0	0	0	0	46
	5	56	53	14	3	0	0	0	0	0	0	0	70
	6	58	22	3	0	0	0	0	0	0	0	0	25
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	1	0	0	0	0	0	0	0	0	0	1
	9	78	0	0	0	0	0	0	0	0	0	0	0
B	1	34	18	0	0	0	0	0	0	0	0	0	18
	2	30	9	2	0	0	0	0	0	0	0	0	11
	3	34	15	3	1	0	0	0	0	0	0	0	19
	4	54	25	7	1	0	0	0	0	0	0	0	33
	5	52	36	8	1	0	0	0	0	0	0	0	45
	6	54	20	2	0	0	0	0	0	0	0	0	22
	7	76	1	0	0	0	0	0	0	0	0	0	1
	8	76	1	0	0	0	0	0	0	0	0	0	1
	9	76	0	0	0	0	0	0	0	0	0	0	0
C	1	39	21	2	1	0	0	0	0	0	0	0	24
	2	36	12	0	0	0	0	0	0	0	0	0	12
	3	39	17	2	0	0	0	0	0	0	0	0	19
	4	58	21	0	0	0	0	0	0	0	0	0	21
	5	56	30	3	1	1	0	0	0	0	0	0	35
	6	58	22	3	2	1	0	0	0	0	0	0	28
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
D	1	34	15	2	0	0	0	0	0	0	0	0	17
	2	30	7	1	0	0	0	0	0	0	0	0	8
	3	34	25	2	0	0	0	0	0	0	0	0	27
	4	54	15	0	0	0	0	0	0	0	0	0	15
	5	52	36	4	0	0	0	0	0	0	0	0	40
	6	54	49	6	0	0	0	0	0	0	0	0	55
	7	76	0	0	0	0	0	0	0	0	0	0	0
	8	76	4	0	0	0	0	0	0	0	0	0	4
	9	76	6	1	0	0	0	0	0	0	0	0	7
E	1	24	74	22	8	3	2	1	0	0	0	0	110
	2	20	107	31	11	4	2	1	1	0	0	0	157
	3	24	64	20	11	6	3	1	1	1	1	1	109
	4	15	76	29	8	4	1	1	0	0	0	0	119
	5	0	61	23	5	2	1	1	0	0	0	0	93
	6	15	83	27	11	6	1	0	0	0	0	0	128
	7	24	23	6	2	1	0	0	0	0	0	0	32
	8	20	55	20	5	1	1	1	1	1	1	0	86
	9	24	64	16	7	1	0	0	0	0	0	0	88

Table A12: Trial 7: 200g PE4, 5cm depth, large stones

Pack / 1	Rectangle / 1	Angle / °	Number of perforation, penetration or witness marks on each layer / 1										Total / 1
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
A	1	39	64	19	4	1	0	0	0	0	0	0	88
	2	36	75	17	6	2	1	0	0	0	0	0	101
	3	39	60	13	2	0	0	0	0	0	0	0	75
	4	58	48	18	4	1	0	0	0	0	0	0	71
	5	56	59	16	5	3	1	1	0	0	0	0	85
	6	58	39	6	2	1	0	0	0	0	0	0	48
	7	78	4	0	0	0	0	0	0	0	0	0	4
	8	78	1	0	0	0	0	0	0	0	0	0	1
	9	78	0	0	0	0	0	0	0	0	0	0	0
B	1	34	45	15	2	1	0	0	0	0	0	0	63
	2	30	56	16	3	1	1	0	0	0	0	0	77
	3	34	50	18	3	0	0	0	0	0	0	0	71
	4	54	39	12	1	0	0	0	0	0	0	0	52
	5	52	58	6	1	0	0	0	0	0	0	0	65
	6	54	46	5	2	0	0	0	0	0	0	0	53
	7	76	2	0	0	0	0	0	0	0	0	0	2
	8	76	9	1	0	0	0	0	0	0	0	0	10
	9	76	11	2	1	0	0	0	0	0	0	0	14
C	1	39	32	3	0	0	0	0	0	0	0	0	35
	2	36	23	1	0	0	0	0	0	0	0	0	24
	3	39	23	1	0	0	0	0	0	0	0	0	24
	4	58	30	2	0	0	0	0	0	0	0	0	32
	5	56	16	1	0	0	0	0	0	0	0	0	17
	6	58	11	1	0	0	0	0	0	0	0	0	12
	7	78	0	0	0	0	0	0	0	0	0	0	0
	8	78	0	0	0	0	0	0	0	0	0	0	0
	9	78	0	0	0	0	0	0	0	0	0	0	0
D	1	34	18	1	0	0	0	0	0	0	0	0	19
	2	30	31	12	3	1	0	0	0	0	0	0	47
	3	34	47	13	3	1	0	0	0	0	0	0	64
	4	54	44	5	1	0	0	0	0	0	0	0	50
	5	52	63	13	2	0	0	0	0	0	0	0	78
	6	54	62	11	2	2	0	0	0	0	0	0	77
	7	76	4	0	0	0	0	0	0	0	0	0	4
	8	76	9	0	0	0	0	0	0	0	0	0	9
	9	76	4	1	0	0	0	0	0	0	0	0	5
E	1	24	134	40	14	5	1	0	0	0	0	0	194
	2	20	148	55	29	14	9	4	0	0	0	0	259
	3	24	146	51	20	8	2	1	0	0	0	0	228
	4	15	136	43	29	8	2	1	0	0	0	0	219
	5	0	194	60	25	13	8	2	2	1	0	0	305
	6	15	244	69	29	12	8	3	1	1	1	0	368
	7	24	92	40	13	6	2	0	0	0	0	0	153
	8	20	127	44	18	10	4	3	1	1	0	0	208
	9	24	147	57	25	9	4	3	2	1	0	0	248

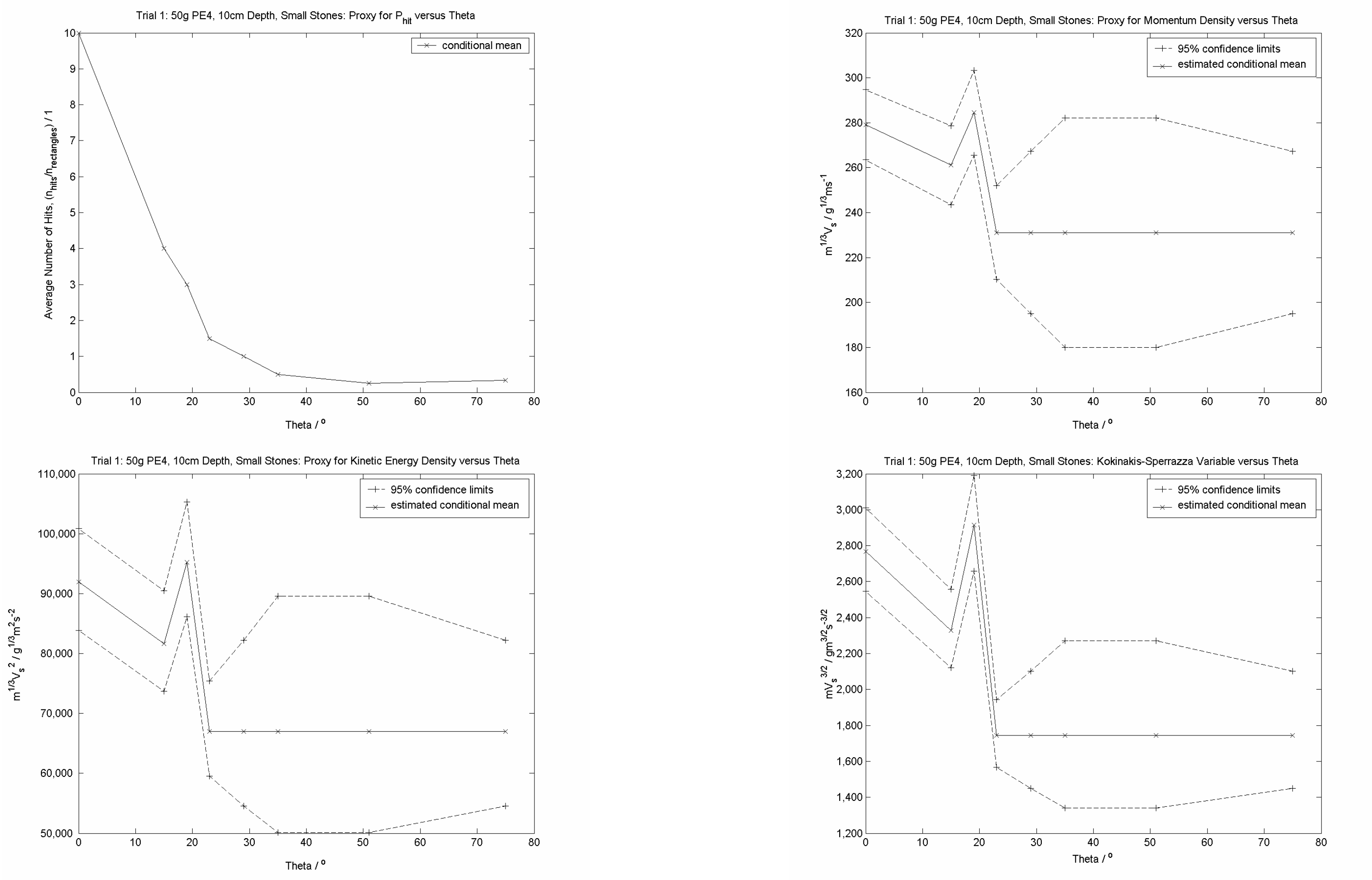
Table A13: Trial 8: 500g PE4, 5cm depth, large stones

A.7 TRIALS DATA TRANSFORMATION (MATLAB® M-FILE)

```
%----------------------------------------------------------------
%Written originally by Dr T Ringrose, Cranfield University.
%Adapted by C Couldrick, Cranfield University.
%Filename is main.m . This file is run after executing the
%calibration transformation file cal.m .
%Estimates the conditional (on an impact being sufficient to
%mark strawboard) mean y value (y0hat) with 95%confidence %limits.
%Choice of calibration model decided previously in cal.m .

%Load raw data for all 8 trials.
      load trials_data;

%Select trial of interest: 1 to 8.
      trial=t1;

%Sort trials data by angle from 0 degrees.
      rawexptdata = sortrows(trial,1);

%Size values of raw data matrix.
      cols = size(rawexptdata,2);
      panels = size(rawexptdata,1);
      maxdepth = cols-2;

%Collates data for the same angle.
      ang = rawexptdata(1,1);
      sec = rawexptdata(1,2:cols);
      j = 1;
      npanels = 1;
      for i=2:panels;
            if rawexptdata(i,1)==ang;
                  sec = sec + rawexptdata(i,2:cols);
                  npanels = npanels+1;
            else
                  exptdata(j,1) = ang;
                  exptdata(j,2:cols) = sec;
                  exptdata(j,cols+1) = npanels;
                  ang = rawexptdata(i,1);
                  sec = rawexptdata(i,2:cols);
                  j = j+1;
                  npanels = 1;
            end;
            exptdata(j,1) = ang;
            exptdata(j,2:cols) = sec;
            exptdata(j,cols+1) = npanels;
      end;

%Removes angles for which zero hits are recorded because the
%mean is conditional.
      b=1;
      for a=1:size(exptdata,1);
            if exptdata(a,2)>0;
                  expt_data(b,:)=exptdata(a,:);
                  b=b+1;
            end;
      end;
      exptdata=expt_data;
```

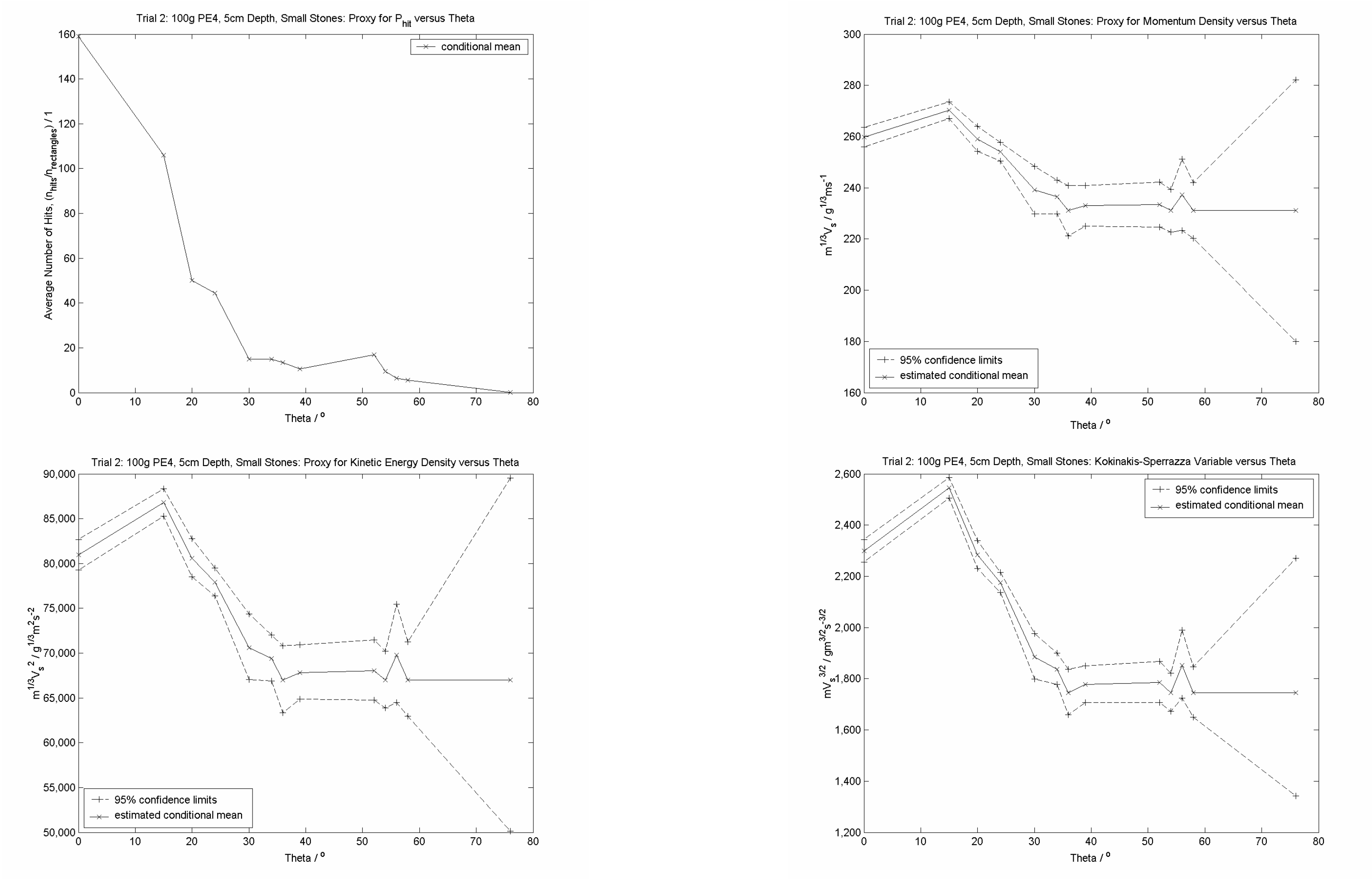
```
      clear expt_data b a;

%Size value of collated data matrix.
      sectors = size(exptdata,1);

%marks = numbers of marks in strawboard.
%d = number of stones hitting exactly that many layers.
%nholes = total number of holes in strawboard (sum of hits).
%nhits = total number of stones (sum of d).
      marks = zeros(sectors,maxdepth);
      d = zeros(sectors,maxdepth);
      marks = exptdata(:,2:cols-1);
      angles = exptdata(:,1);
      nhits = exptdata(:,2);
      nmarks = exptdata(:,cols);
      d(:,maxdepth) = marks(:,maxdepth);
      nrectangles = exptdata(:,cols+1);
      for i=1:maxdepth-1;
            d(:,i) = marks(:,i)-marks(:,i+1);
      end;

      varyhat = sds.^2;

      sectorvar = d*varyhat(1:maxdepth) ./ (n.^2+(n==0));
      sectorave  =  (  nhits.*betahat(1)  +  nmarks.*betahat(2)  )  ./
      (nhits+(nhits==0));

%The output is trial results of the angle, number of stones.
%hitting at that angle, the conditional mean, variance, lower &
%upper 95% confidence limits, average number of hits (i.e. stone
%impacts per rectangle).
      results = zeros(sectors,6);
      results(:,1) = angles;
      results(:,2) = nhits;
      results(:,3) = sectorave;
      results(:,4) = sectorvar;
      results(:,5) = sectorave-tcrit*sqrt(sectorvar);
      results(:,6) = sectorave+tcrit*sqrt(sectorvar);
      results(:,7) = nhits./nrectangles;
%----------------------------------------------------------------
```

A.8 TRIALS RESULTS



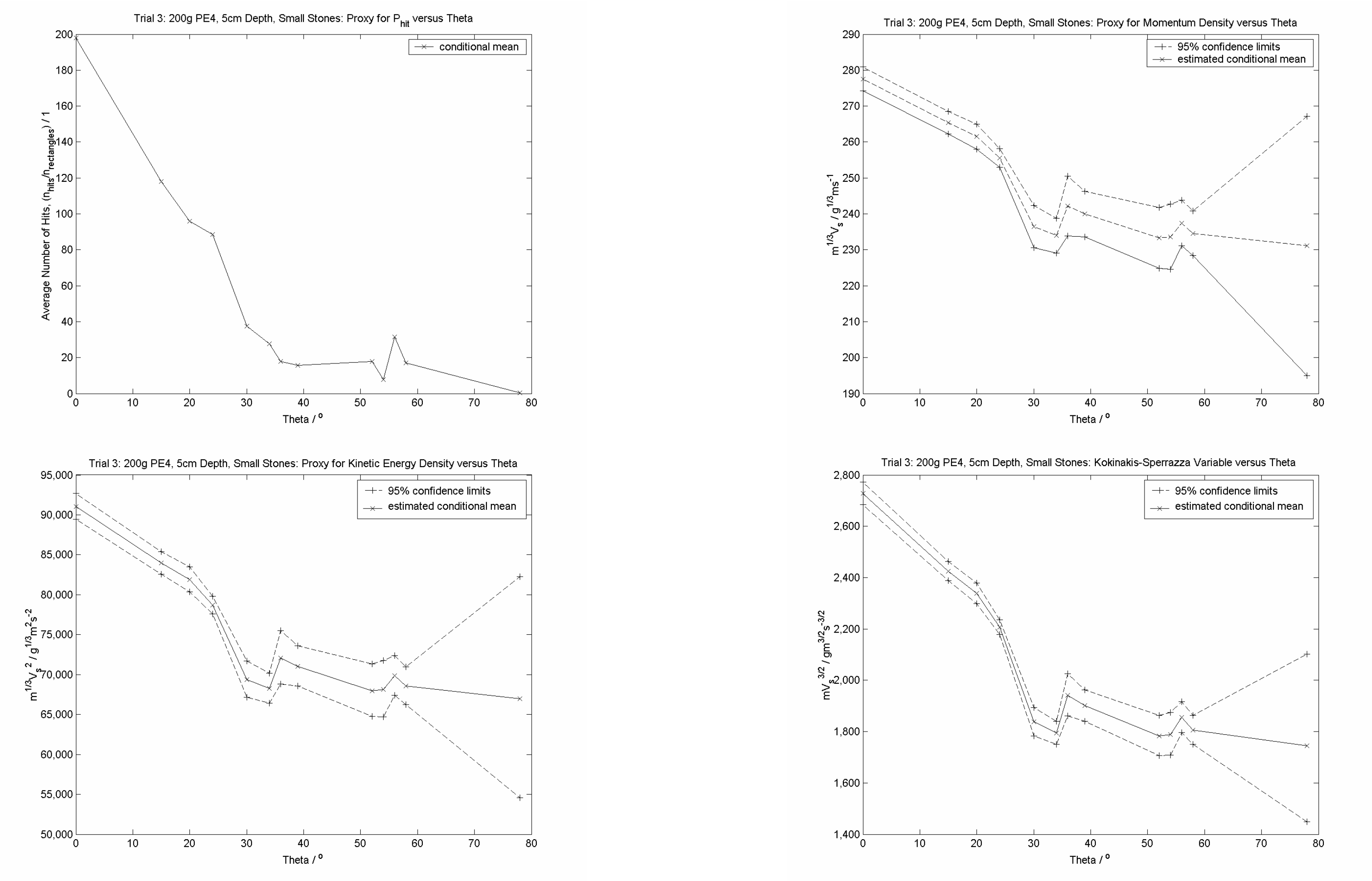
NB conditional on impacts marking strawboard

Figures A4a, b, c & d: Trial 1 results



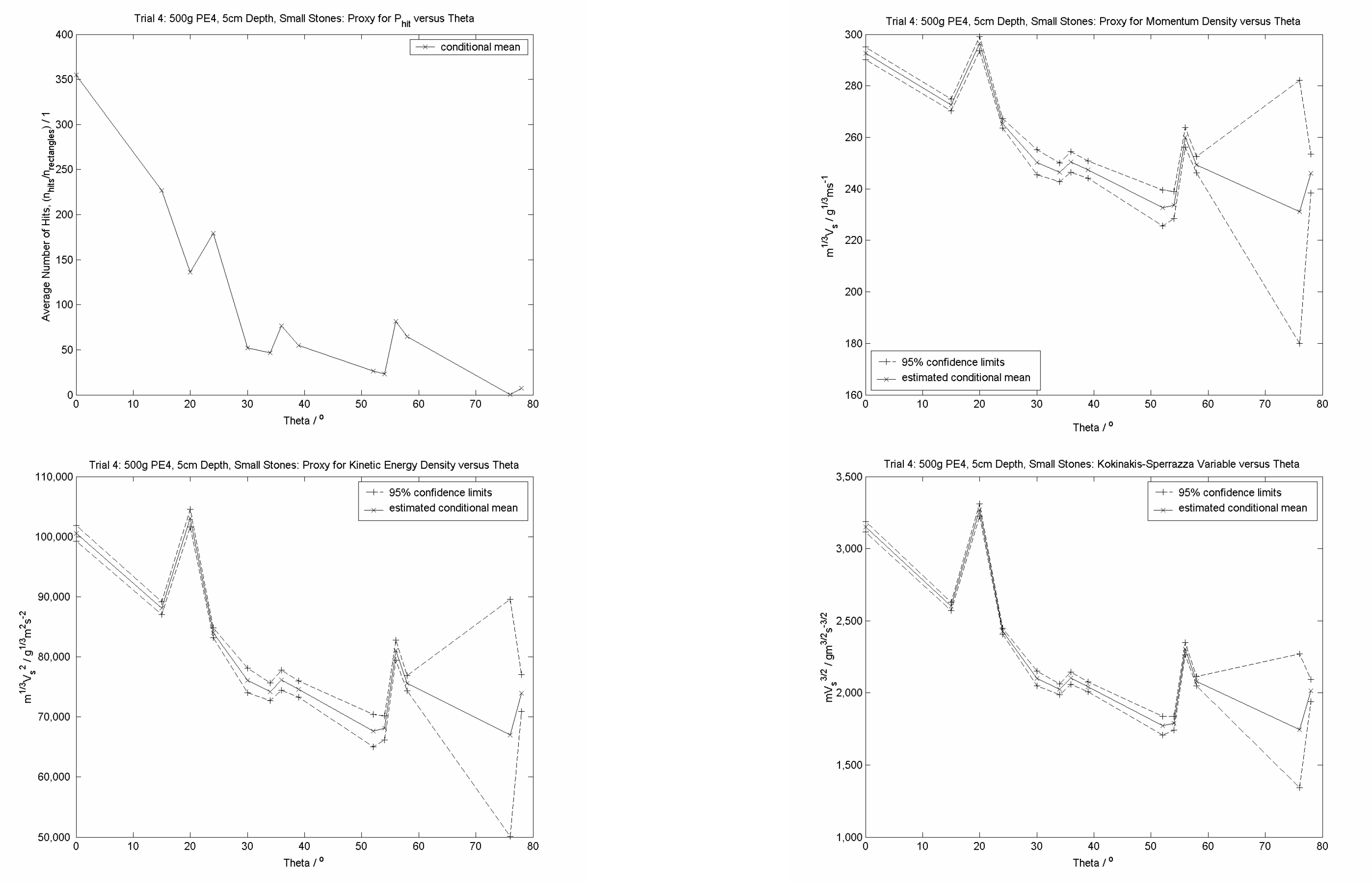
NB conditional on impacts marking strawboard

Figures A5a, b, c & d: Trial 2 results



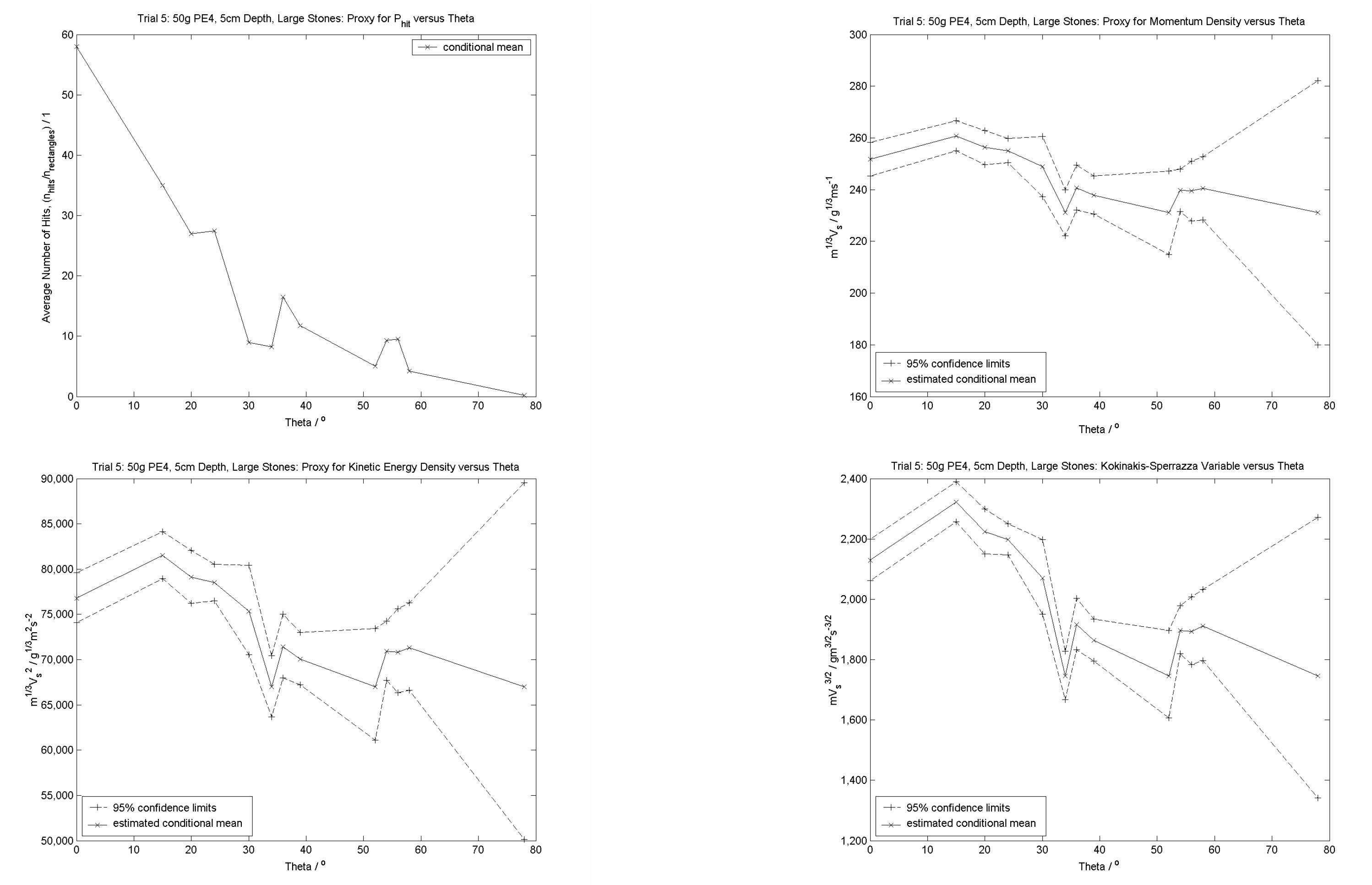
NB conditional on impacts marking strawboard

Figures A6a, b, c & d: Trial 3 results



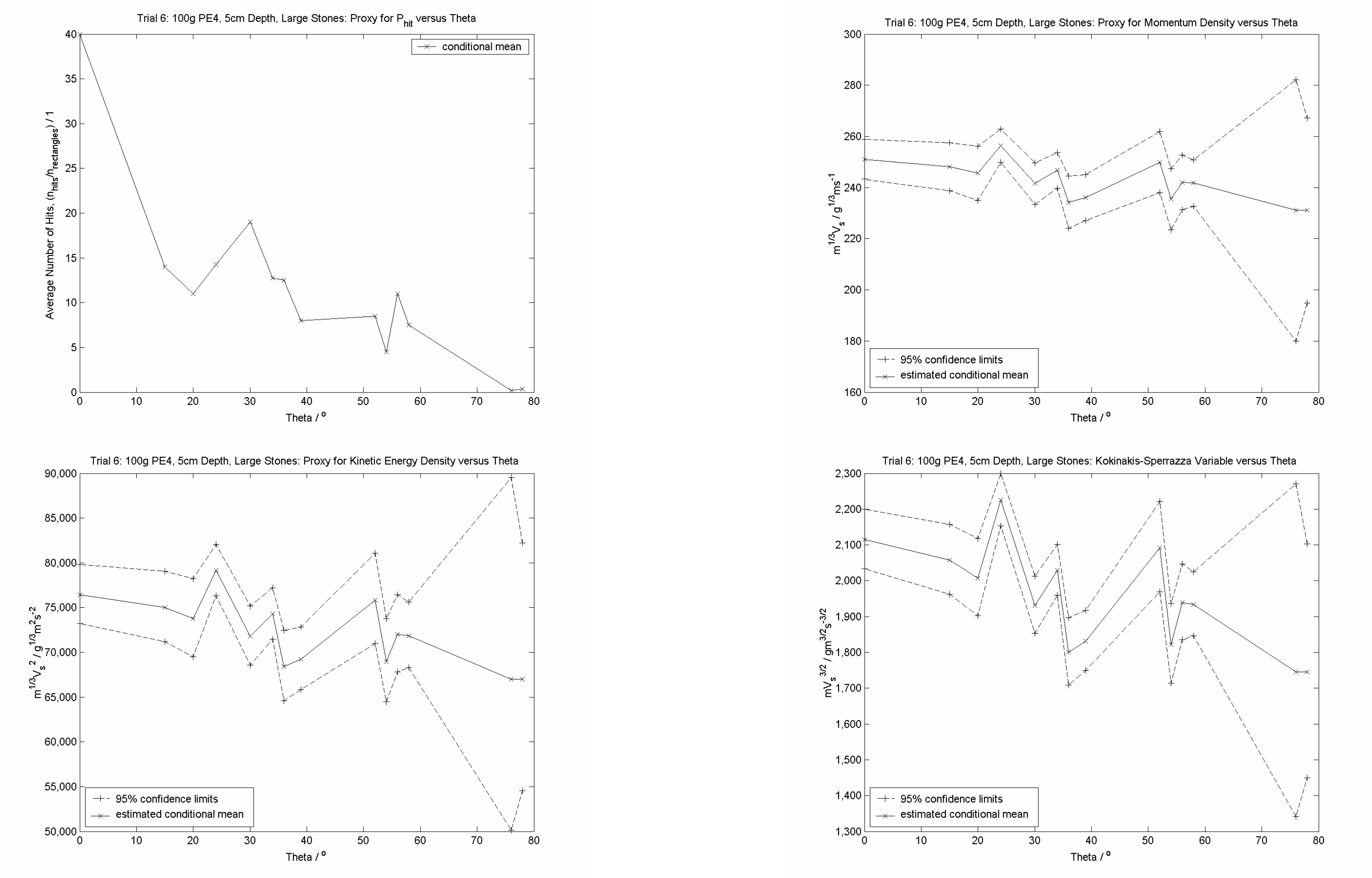
NB conditional on impacts marking strawboard

Figures A7a, b, c & d: Trial 4 results



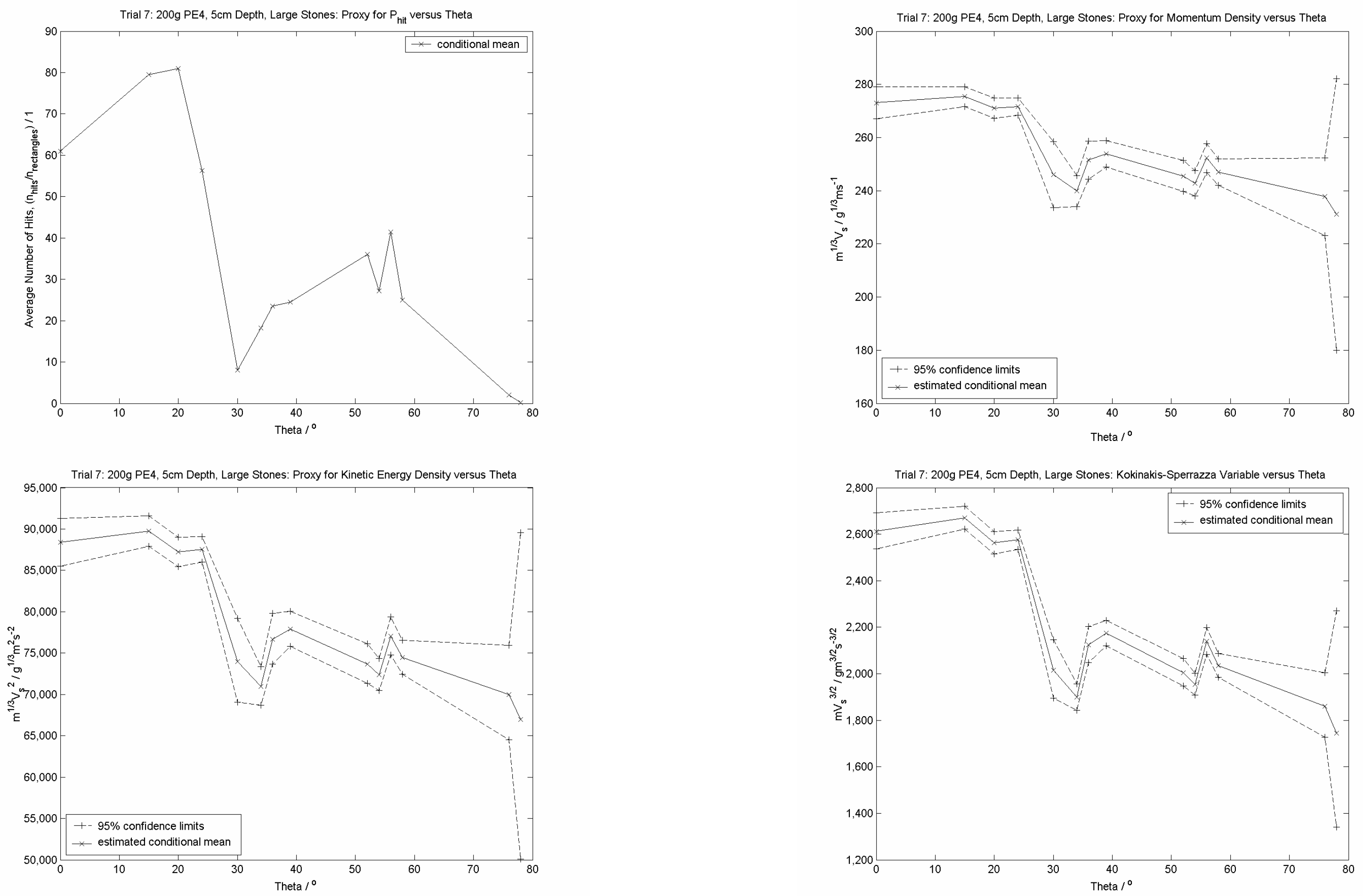
NB conditional on impacts marking strawboard

Figures A8a, b, c & d: Trial 5 results



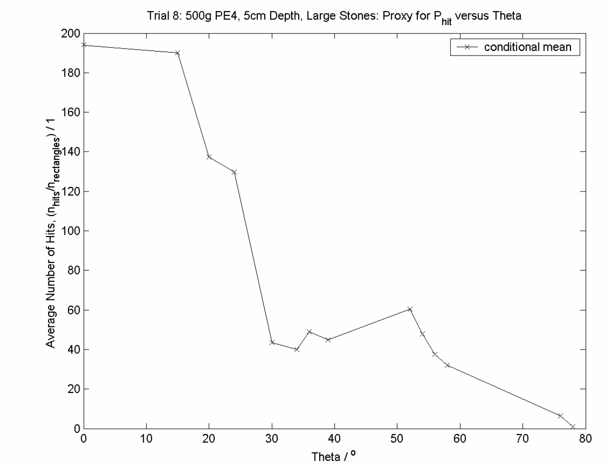
NB conditional on impacts marking strawboard

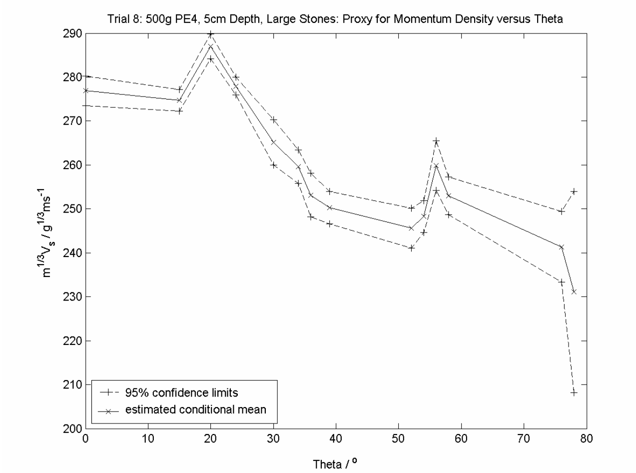
Figures A9a, b, c & d: Trial 6 results

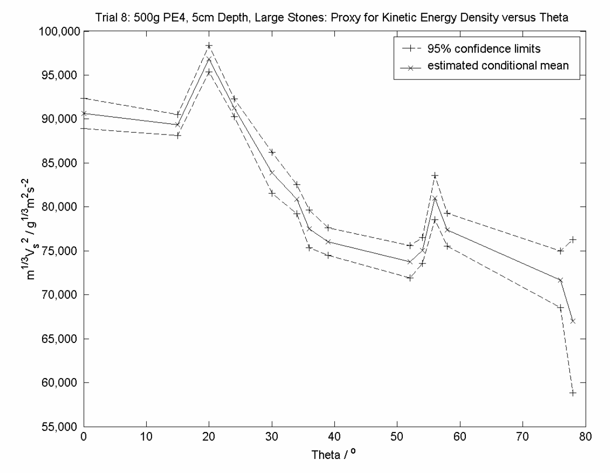


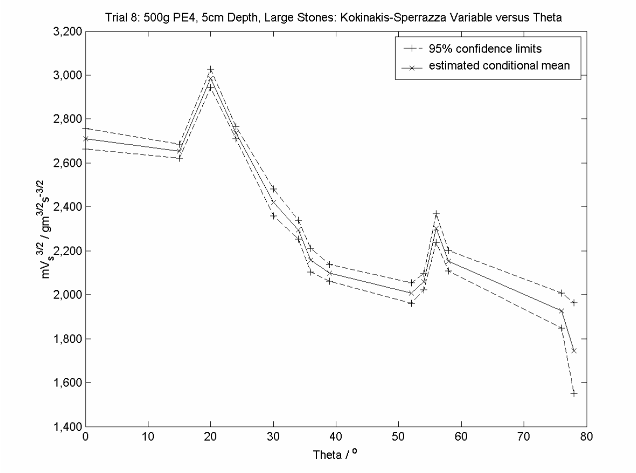
NB conditional on impacts marking strawboard

Figures A10a, b, c & d: Trial 7 results









NB conditional on impacts marking strawboard

Figures A11a, b, c & d: Trial 8 results

APPENDIX B: ASSESSMENT OF PROTECTION LIMITS FOR THE LIGHTWEIGHT COMBAT EOD SUIT

B.1 VISOR GEOMETRY – cachelm.geo

The visor geometry is altered from the standard file to represent the tapered design (CASPER part 7010) of the lightweight EOD suit. The *.geo file is modified by hand, replacing six triangles at each side of the visor with one. This is shown in Figure B1 by joining nodes A, B and C directly. The numerical changes to the CASPER *.geo file are stored in cachelm.geo and presented below.

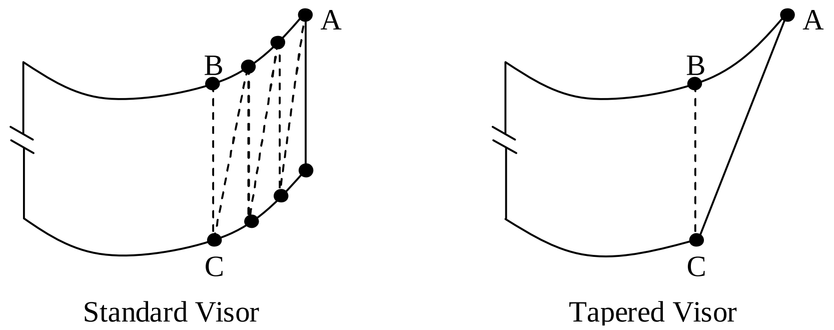


Figure B1: The tapered visor is a modification of the CASPER standard design

```
-37
 7010
  100
    3
   78    -129    1309
  -45     -46    1206
   73    -136    1309
  -50     -54    1206
   68    -143    1310
  -55     -60    1207
   60    -147    1311
  -60     -66    1209
   54    -153    1313
  -66     -72    1211
   47    -159    1315
  -73     -78    1214
   39    -162    1318
  -79     -82    1218
   32    -167    1319
  -85     -88    1221
   24    -170    1324
  -92     -92    1226
   16    -172    1327
  -98     -95    1231
```

8	-173	1330
-104	-98	1236
0	-174	1335
-110	-100	1241
-8	-176	1339
-117	-102	1247
-18	-174	1344
-124	-103	1254
-26	-174	1349
-130	-104	1261
-33	-172	1354
-135	-103	1268
-40	-170	1357
-139	-103	1273
-48	-166	1363
-145	-101	1281
-91	-138	1397
-37		
7010		
100		
3		
78	-129	1309
-45	-46	1206
83	-121	1309
-40	-39	1206
87	-114	1310
-36	-32	1207
88	-106	1311
-32	-24	1209
91	-98	1313
-29	-17	1211
94	-89	1315
-26	-8	1214
94	-81	1318
-24	0	1218
96	-72	1319
-21	7	1221
96	-64	1324
-20	14	1226
94	-56	1327
-20	21	1231
93	-47	1330
-19	28	1236
91	-40	1335
-20	35	1241
89	-31	1339
-20	42	1247
84	-23	1344
-22	48	1254
81	-16	1349
-23	54	1261
76	-10	1354
-25	59	1268
72	-4	1357
-28	63	1273
65	1	1363
-32	67	1281
23	31	1397

B.2 OUTPUT FROM CASPER TRANSFORMED IN EXCEL®

BL755 Sub-munition: For all approach angles (roll), ϑ				
r / m	**$Pc_{unarmoured}$ / 1**	**$UF_{casualty}$ / 1**	**$UF_{serious}$ / 1**	**UF_{lethal} / 1**
0	1.000	0.000	0.000	0.000
1.5	1.000	0.000	0.000	0.002
3	1.000	0.000	0.000	0.028
4.5	1.000	0.000	0.003	0.155
6	0.998	0.002	0.035	0.208
7.5	0.971	0.020	0.052	0.112
9	0.903	0.022	0.066	0.093
10.5	0.791	0.072	0.102	0.075
12	0.644	0.082	0.097	0.062
13.5	0.515	0.079	0.083	0.047
15	0.409	0.067	0.094	0.028
16.5	0.347	0.099	0.074	0.020
18	0.301	0.083	0.059	0.013
19.5	0.264	0.072	0.049	0.010
21	0.234	0.064	0.042	0.008
22.5	0.209	0.059	0.037	0.006
24	0.190	0.055	0.034	0.005
25.5	0.175	0.053	0.031	0.002
27	0.161	0.051	0.029	0.002
28.5	0.148	0.048	0.026	0.002
30	0.137	0.046	0.024	0.001

Table B1: BL755 sub-munition results

HB876 Area Denial Mine: For all approach angles (roll), ϑ				
r / m	**$Pc_{unarmoured}$ / 1**	**$UF_{casualty}$ / 1**	**$UF_{serious}$ / 1**	**UF_{lethal} / 1**
0	1.000	0.000	0.000	0.000
1.5	0.698	0.000	0.000	0.000
3	0.467	0.000	0.000	0.000
4.5	0.357	0.000	0.000	0.000
6	0.309	0.003	0.003	0.003
7.5	0.268	0.004	0.004	0.004
9	0.231	0.004	0.004	0.004
10.5	0.205	0.006	0.006	0.005
12	0.184	0.008	0.008	0.006
13.5	0.167	0.009	0.009	0.007
15	0.150	0.010	0.009	0.007
16.5	0.132	0.009	0.008	0.006
18	0.116	0.007	0.007	0.005
19.5	0.102	0.006	0.006	0.005
21	0.089	0.006	0.006	0.004
22.5	0.079	0.005	0.005	0.004
24	0.071	0.004	0.004	0.003
25.5	0.065	0.004	0.004	0.003
27	0.060	0.005	0.004	0.003
28.5	0.055	0.005	0.004	0.003
30	0.050	0.004	0.004	0.003

Table B2: HB876 area denial weapon results

r / m	$Pc_{unarmoured}$ / 1 for L2A2 Grenade — Approach angle (yaw), ϑ / º																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999
2	0.000	0.000	0.470	1.000	0.998	1.000	1.000	1.000	1.000	0.990	0.949	0.686	0.604	0.756	0.946	0.990	1.000	1.000	1.000	1.000	0.998	1.000	0.505	0.008	0.000
3	0.000	0.000	0.000	0.987	0.938	0.999	0.994	0.997	0.988	0.874	0.734	0.134	0.168	0.157	0.714	0.877	0.988	0.994	0.993	0.999	0.953	0.973	0.010	0.000	0.000
4	0.000	0.000	0.000	0.892	0.798	0.983	0.942	0.966	0.925	0.696	0.544	0.028	0.146	0.029	0.559	0.704	0.923	0.946	0.933	0.983	0.835	0.834	0.000	0.000	0.000
5	0.000	0.000	0.000	0.748	0.648	0.929	0.844	0.887	0.816	0.537	0.390	0.020	0.123	0.020	0.421	0.543	0.806	0.853	0.827	0.924	0.694	0.667	0.000	0.000	0.000
6	0.000	0.000	0.000	0.612	0.526	0.852	0.743	0.777	0.692	0.424	0.291	0.018	0.082	0.015	0.324	0.421	0.688	0.751	0.722	0.832	0.565	0.537	0.000	0.000	0.000
7	0.000	0.000	0.000	0.503	0.430	0.776	0.613	0.672	0.575	0.337	0.221	0.017	0.048	0.012	0.251	0.337	0.581	0.664	0.592	0.736	0.457	0.431	0.000	0.000	0.000
8	0.000	0.000	0.000	0.411	0.362	0.670	0.508	0.581	0.473	0.264	0.174	0.016	0.030	0.011	0.197	0.273	0.498	0.557	0.489	0.643	0.369	0.334	0.000	0.000	0.000
9	0.000	0.000	0.000	0.334	0.306	0.557	0.434	0.502	0.409	0.216	0.136	0.014	0.022	0.009	0.159	0.222	0.426	0.456	0.417	0.560	0.316	0.270	0.000	0.000	0.000
10	0.000	0.000	0.000	0.284	0.258	0.477	0.368	0.423	0.347	0.175	0.109	0.012	0.017	0.008	0.128	0.189	0.364	0.386	0.354	0.474	0.265	0.216	0.000	0.000	0.000
11	0.000	0.000	0.000	0.244	0.217	0.413	0.308	0.360	0.292	0.145	0.089	0.011	0.013	0.007	0.106	0.162	0.310	0.333	0.298	0.405	0.221	0.176	0.000	0.000	0.000
12	0.000	0.000	0.000	0.210	0.179	0.359	0.260	0.313	0.254	0.122	0.074	0.010	0.009	0.006	0.089	0.140	0.258	0.286	0.252	0.354	0.191	0.147	0.000	0.000	0.000
13	0.000	0.000	0.000	0.184	0.151	0.313	0.224	0.276	0.222	0.104	0.062	0.010	0.005	0.006	0.077	0.122	0.218	0.249	0.217	0.312	0.167	0.124	0.000	0.000	0.000
14	0.000	0.000	0.000	0.159	0.130	0.277	0.195	0.244	0.193	0.091	0.053	0.010	0.003	0.006	0.068	0.106	0.188	0.220	0.189	0.278	0.145	0.108	0.000	0.000	0.000
15	0.000	0.000	0.000	0.138	0.112	0.243	0.171	0.216	0.169	0.080	0.045	0.009	0.002	0.005	0.060	0.091	0.163	0.193	0.165	0.246	0.127	0.095	0.000	0.000	0.000
16	0.000	0.000	0.000	0.121	0.100	0.216	0.154	0.192	0.151	0.071	0.039	0.009	0.001	0.005	0.053	0.080	0.145	0.171	0.148	0.219	0.114	0.084	0.000	0.000	0.000
17	0.000	0.000	0.000	0.106	0.090	0.194	0.139	0.170	0.134	0.064	0.034	0.008	0.000	0.005	0.047	0.070	0.131	0.153	0.134	0.194	0.101	0.074	0.000	0.000	0.000
18	0.000	0.000	0.000	0.092	0.082	0.176	0.127	0.153	0.119	0.057	0.031	0.008	0.000	0.004	0.041	0.062	0.119	0.138	0.121	0.173	0.089	0.067	0.000	0.000	0.000
19	0.000	0.000	0.000	0.082	0.075	0.160	0.116	0.138	0.107	0.052	0.028	0.007	0.000	0.004	0.036	0.055	0.108	0.125	0.111	0.156	0.080	0.060	0.000	0.000	0.000
20	0.000	0.000	0.000	0.073	0.068	0.146	0.106	0.125	0.097	0.047	0.024	0.006	0.000	0.004	0.032	0.049	0.098	0.112	0.101	0.141	0.072	0.054	0.000	0.000	0.000

Table B3: L2A2 grenade results: $P_{c\ unarmoured}$

	$UF_{casualty}$ / 1 for L2A2 Grenade																								
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
2	0.000	0.000	0.022	0.000	0.001	0.000	0.000	0.000	0.000	0.003	0.009	0.055	0.026	0.043	0.010	0.003	0.000	0.000	0.000	0.000	0.001	0.000	0.019	0.001	0.000
3	0.000	0.000	0.000	0.004	0.010	0.000	0.002	0.001	0.004	0.018	0.021	0.008	0.000	0.008	0.022	0.018	0.004	0.002	0.003	0.000	0.008	0.008	0.001	0.000	0.000
4	0.000	0.000	0.000	0.019	0.018	0.004	0.009	0.006	0.012	0.024	0.026	0.000	0.008	0.000	0.025	0.024	0.013	0.009	0.011	0.004	0.015	0.028	0.000	0.000	0.000
5	0.000	0.000	0.000	0.028	0.025	0.015	0.017	0.018	0.023	0.025	0.024	0.000	0.013	0.000	0.023	0.024	0.024	0.022	0.019	0.017	0.023	0.038	0.000	0.000	0.000
6	0.000	0.000	0.000	0.030	0.020	0.020	0.023	0.023	0.022	0.023	0.021	0.000	0.009	0.000	0.020	0.023	0.021	0.026	0.025	0.022	0.020	0.036	0.000	0.000	0.000
7	0.000	0.000	0.000	0.028	0.022	0.026	0.021	0.026	0.030	0.019	0.017	0.000	0.003	0.000	0.016	0.020	0.029	0.028	0.022	0.029	0.022	0.031	0.000	0.000	0.000
8	0.000	0.000	0.000	0.026	0.023	0.033	0.023	0.034	0.032	0.019	0.016	0.000	0.003	0.000	0.016	0.018	0.030	0.035	0.024	0.036	0.023	0.030	0.000	0.000	0.000
9	0.000	0.000	0.000	0.035	0.040	0.049	0.040	0.050	0.045	0.029	0.022	0.000	0.005	0.000	0.022	0.027	0.049	0.053	0.044	0.067	0.033	0.048	0.000	0.000	0.000
10	0.000	0.000	0.000	0.032	0.038	0.045	0.042	0.043	0.049	0.024	0.018	0.000	0.004	0.000	0.018	0.023	0.055	0.048	0.046	0.059	0.031	0.042	0.000	0.000	0.000
11	0.000	0.000	0.000	0.029	0.032	0.047	0.036	0.037	0.040	0.020	0.015	0.000	0.003	0.000	0.014	0.021	0.047	0.048	0.039	0.049	0.024	0.033	0.000	0.000	0.000
12	0.000	0.000	0.000	0.025	0.026	0.041	0.033	0.033	0.041	0.017	0.013	0.000	0.003	0.000	0.011	0.019	0.039	0.040	0.036	0.043	0.024	0.029	0.000	0.000	0.000
13	0.000	0.000	0.000	0.057	0.046	0.069	0.055	0.074	0.074	0.033	0.022	0.001	0.002	0.001	0.023	0.038	0.065	0.072	0.056	0.074	0.052	0.048	0.000	0.000	0.000
14	0.000	0.000	0.000	0.050	0.040	0.068	0.050	0.069	0.065	0.030	0.020	0.001	0.002	0.001	0.022	0.034	0.056	0.067	0.050	0.075	0.046	0.044	0.000	0.000	0.000
15	0.000	0.000	0.000	0.044	0.037	0.075	0.049	0.066	0.057	0.029	0.018	0.001	0.002	0.001	0.021	0.031	0.051	0.064	0.049	0.080	0.041	0.041	0.000	0.000	0.000
16	0.000	0.000	0.000	0.039	0.034	0.066	0.044	0.058	0.052	0.026	0.016	0.002	0.001	0.001	0.019	0.027	0.047	0.057	0.044	0.070	0.038	0.037	0.000	0.000	0.000
17	0.000	0.000	0.000	0.034	0.032	0.059	0.040	0.051	0.046	0.024	0.014	0.002	0.000	0.001	0.017	0.024	0.044	0.051	0.040	0.061	0.034	0.033	0.000	0.000	0.000
18	0.000	0.000	0.000	0.030	0.030	0.053	0.036	0.044	0.041	0.021	0.013	0.002	0.000	0.001	0.015	0.021	0.042	0.046	0.036	0.052	0.030	0.030	0.000	0.000	0.000
19	0.000	0.000	0.000	0.027	0.028	0.048	0.033	0.039	0.037	0.019	0.012	0.002	0.000	0.001	0.013	0.019	0.039	0.041	0.033	0.046	0.027	0.027	0.000	0.000	0.000
20	0.000	0.000	0.000	0.024	0.026	0.043	0.030	0.035	0.034	0.017	0.010	0.002	0.000	0.001	0.011	0.017	0.035	0.036	0.030	0.041	0.025	0.024	0.000	0.000	0.000

Table B4: L2A2 grenade results: $UF_{casualty}$

$UF_{serious}$ / 1 for L2A2 Grenade																									
r / m	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.008	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.006	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.008	0.008
2	0.000	0.000	0.025	0.001	0.006	0.000	0.001	0.000	0.001	0.012	0.022	0.062	0.032	0.053	0.023	0.012	0.002	0.001	0.001	0.000	0.005	0.003	0.031	0.001	0.000
3	0.000	0.000	0.000	0.016	0.024	0.004	0.011	0.006	0.016	0.031	0.028	0.010	0.001	0.009	0.028	0.030	0.016	0.011	0.013	0.005	0.020	0.027	0.001	0.000	0.000
4	0.000	0.000	0.000	0.036	0.028	0.017	0.023	0.018	0.029	0.032	0.029	0.001	0.006	0.000	0.028	0.032	0.029	0.025	0.025	0.017	0.025	0.047	0.000	0.000	0.000
5	0.000	0.000	0.000	0.042	0.033	0.035	0.031	0.035	0.039	0.029	0.025	0.000	0.010	0.000	0.025	0.029	0.040	0.041	0.033	0.038	0.031	0.050	0.000	0.000	0.000
6	0.000	0.000	0.000	0.041	0.026	0.040	0.035	0.037	0.037	0.026	0.022	0.000	0.008	0.000	0.021	0.026	0.036	0.042	0.038	0.041	0.026	0.046	0.000	0.000	0.000
7	0.000	0.000	0.000	0.037	0.028	0.049	0.032	0.040	0.039	0.023	0.019	0.000	0.004	0.000	0.018	0.023	0.039	0.048	0.034	0.049	0.027	0.039	0.000	0.000	0.000
8	0.000	0.000	0.000	0.040	0.033	0.056	0.035	0.051	0.043	0.026	0.021	0.000	0.003	0.000	0.020	0.026	0.044	0.058	0.040	0.062	0.030	0.045	0.000	0.000	0.000
9	0.000	0.000	0.000	0.032	0.034	0.052	0.038	0.050	0.043	0.023	0.017	0.000	0.003	0.000	0.017	0.022	0.048	0.050	0.041	0.069	0.029	0.039	0.000	0.000	0.000
10	0.000	0.000	0.000	0.027	0.032	0.046	0.038	0.041	0.040	0.020	0.014	0.000	0.003	0.000	0.014	0.019	0.047	0.044	0.040	0.057	0.026	0.032	0.000	0.000	0.000
11	0.000	0.000	0.000	0.025	0.027	0.045	0.032	0.035	0.034	0.016	0.012	0.000	0.002	0.000	0.011	0.018	0.040	0.043	0.034	0.047	0.022	0.026	0.000	0.000	0.000
12	0.000	0.000	0.000	0.024	0.024	0.042	0.031	0.034	0.036	0.015	0.011	0.000	0.002	0.000	0.010	0.017	0.035	0.039	0.033	0.044	0.023	0.024	0.000	0.000	0.000
13	0.000	0.000	0.000	0.040	0.031	0.055	0.041	0.055	0.050	0.022	0.014	0.001	0.002	0.000	0.016	0.026	0.044	0.050	0.040	0.058	0.036	0.029	0.000	0.000	0.000
14	0.000	0.000	0.000	0.035	0.027	0.059	0.039	0.053	0.043	0.020	0.012	0.001	0.002	0.000	0.015	0.023	0.037	0.047	0.038	0.063	0.032	0.026	0.000	0.000	0.000
15	0.000	0.000	0.000	0.029	0.023	0.051	0.033	0.046	0.036	0.018	0.010	0.001	0.001	0.001	0.013	0.019	0.032	0.041	0.032	0.055	0.027	0.023	0.000	0.000	0.000
16	0.000	0.000	0.000	0.026	0.021	0.044	0.029	0.039	0.032	0.016	0.009	0.001	0.000	0.001	0.012	0.017	0.029	0.035	0.028	0.047	0.025	0.020	0.000	0.000	0.000
17	0.000	0.000	0.000	0.022	0.019	0.038	0.025	0.033	0.028	0.013	0.008	0.002	0.000	0.001	0.010	0.014	0.026	0.030	0.025	0.039	0.021	0.017	0.000	0.000	0.000
18	0.000	0.000	0.000	0.019	0.017	0.033	0.022	0.027	0.024	0.012	0.007	0.001	0.000	0.001	0.008	0.013	0.024	0.026	0.022	0.032	0.019	0.015	0.000	0.000	0.000
19	0.000	0.000	0.000	0.016	0.015	0.029	0.020	0.024	0.020	0.010	0.006	0.001	0.000	0.000	0.008	0.011	0.021	0.023	0.019	0.028	0.016	0.013	0.000	0.000	0.000
20	0.000	0.000	0.000	0.014	0.013	0.025	0.017	0.021	0.018	0.009	0.005	0.001	0.000	0.000	0.007	0.010	0.018	0.020	0.016	0.024	0.014	0.011	0.000	0.000	0.000

Table B5: L2A2 grenade results: $UF_{serious}$

UF_{lethal} / 1 for L2A2 Grenade																									
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.095	0.102	0.093	0.096	0.065	0.069	0.084	0.073	0.071	0.099	0.081	0.092	0.097	0.094	0.086	0.086	0.056	0.089	0.080	0.072	0.070	0.077	0.141	0.115	0.095
2	0.000	0.000	0.017	0.089	0.063	0.087	0.081	0.072	0.079	0.058	0.043	0.041	0.023	0.042	0.044	0.055	0.080	0.081	0.082	0.086	0.062	0.101	0.027	0.001	0.000
3	0.000	0.000	0.000	0.065	0.043	0.084	0.071	0.062	0.064	0.037	0.023	0.006	0.001	0.005	0.022	0.038	0.065	0.066	0.072	0.084	0.043	0.070	0.001	0.000	0.000
4	0.000	0.000	0.000	0.047	0.028	0.063	0.045	0.047	0.047	0.025	0.018	0.001	0.003	0.000	0.018	0.025	0.047	0.049	0.046	0.063	0.028	0.048	0.000	0.000	0.000
5	0.000	0.000	0.000	0.036	0.024	0.056	0.035	0.043	0.038	0.019	0.014	0.000	0.004	0.000	0.014	0.019	0.037	0.045	0.036	0.058	0.024	0.036	0.000	0.000	0.000
6	0.000	0.000	0.000	0.028	0.018	0.046	0.029	0.034	0.028	0.015	0.012	0.000	0.004	0.000	0.012	0.015	0.028	0.037	0.030	0.045	0.018	0.029	0.000	0.000	0.000
7	0.000	0.000	0.000	0.028	0.020	0.055	0.027	0.035	0.031	0.016	0.011	0.000	0.003	0.000	0.011	0.015	0.030	0.049	0.031	0.048	0.019	0.028	0.000	0.000	0.000
8	0.000	0.000	0.000	0.021	0.017	0.041	0.022	0.031	0.022	0.013	0.010	0.000	0.002	0.000	0.009	0.013	0.023	0.035	0.024	0.044	0.015	0.022	0.000	0.000	0.000
9	0.000	0.000	0.000	0.014	0.016	0.030	0.019	0.028	0.019	0.010	0.007	0.000	0.002	0.000	0.008	0.009	0.022	0.026	0.020	0.042	0.013	0.018	0.000	0.000	0.000
10	0.000	0.000	0.000	0.011	0.014	0.025	0.016	0.022	0.016	0.009	0.006	0.000	0.001	0.000	0.006	0.008	0.019	0.022	0.017	0.032	0.011	0.014	0.000	0.000	0.000
11	0.000	0.000	0.000	0.011	0.013	0.024	0.014	0.018	0.014	0.007	0.005	0.000	0.001	0.000	0.005	0.008	0.017	0.022	0.016	0.024	0.010	0.011	0.000	0.000	0.000
12	0.000	0.000	0.000	0.009	0.010	0.019	0.014	0.014	0.014	0.006	0.005	0.000	0.001	0.000	0.003	0.007	0.013	0.016	0.014	0.019	0.010	0.010	0.000	0.000	0.000
13	0.000	0.000	0.000	0.008	0.008	0.017	0.012	0.013	0.013	0.005	0.004	0.000	0.001	0.000	0.003	0.006	0.011	0.014	0.013	0.018	0.009	0.008	0.000	0.000	0.000
14	0.000	0.000	0.000	0.006	0.007	0.015	0.009	0.011	0.009	0.004	0.003	0.000	0.001	0.000	0.003	0.005	0.008	0.012	0.009	0.016	0.007	0.007	0.000	0.000	0.000
15	0.000	0.000	0.000	0.005	0.005	0.013	0.006	0.010	0.007	0.004	0.003	0.000	0.000	0.000	0.002	0.004	0.006	0.010	0.007	0.014	0.006	0.006	0.000	0.000	0.000
16	0.000	0.000	0.000	0.004	0.004	0.010	0.006	0.008	0.006	0.004	0.002	0.000	0.000	0.000	0.002	0.003	0.005	0.008	0.006	0.011	0.005	0.005	0.000	0.000	0.000
17	0.000	0.000	0.000	0.003	0.003	0.008	0.005	0.006	0.005	0.003	0.002	0.000	0.000	0.000	0.002	0.002	0.004	0.006	0.005	0.009	0.004	0.004	0.000	0.000	0.000
18	0.000	0.000	0.000	0.002	0.003	0.007	0.004	0.005	0.004	0.003	0.001	0.000	0.000	0.000	0.002	0.002	0.004	0.005	0.004	0.007	0.003	0.003	0.000	0.000	0.000
19	0.000	0.000	0.000	0.002	0.003	0.005	0.003	0.004	0.003	0.002	0.001	0.000	0.000	0.000	0.001	0.002	0.003	0.004	0.003	0.005	0.002	0.003	0.000	0.000	0.000
20	0.000	0.000	0.000	0.001	0.002	0.004	0.002	0.003	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.002	0.002	0.003	0.002	0.004	0.002	0.002	0.000	0.000	0.000

Table B6: L2A2 grenade results: UF_{lethal}

$Pc_{unarmoured}$ / 1 for No. 36 Mills Grenade																									
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.948	0.965	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.998	0.961	0.948
3	0.687	0.709	0.926	0.990	0.987	1.000	1.000	0.994	0.984	0.985	0.988	0.964	0.943	0.981	0.986	0.984	0.989	0.997	0.999	0.999	0.981	0.990	0.904	0.636	0.687
4	0.511	0.449	0.710	0.930	0.912	0.990	0.985	0.948	0.908	0.906	0.929	0.781	0.758	0.823	0.920	0.894	0.924	0.963	0.983	0.982	0.898	0.932	0.696	0.377	0.511
5	0.426	0.242	0.522	0.820	0.786	0.947	0.934	0.844	0.789	0.788	0.824	0.525	0.636	0.571	0.810	0.765	0.805	0.879	0.929	0.918	0.774	0.826	0.510	0.208	0.426
6	0.321	0.122	0.410	0.699	0.664	0.879	0.863	0.723	0.657	0.676	0.719	0.363	0.547	0.351	0.701	0.639	0.684	0.781	0.854	0.823	0.642	0.717	0.394	0.135	0.321
7	0.226	0.086	0.323	0.595	0.554	0.808	0.750	0.619	0.538	0.569	0.621	0.263	0.469	0.257	0.592	0.538	0.573	0.695	0.740	0.728	0.524	0.610	0.311	0.100	0.226
8	0.169	0.070	0.258	0.507	0.472	0.704	0.645	0.523	0.437	0.471	0.529	0.209	0.409	0.208	0.500	0.455	0.490	0.585	0.635	0.631	0.424	0.507	0.250	0.084	0.169
9	0.141	0.058	0.213	0.428	0.401	0.586	0.565	0.445	0.374	0.398	0.449	0.172	0.367	0.170	0.431	0.383	0.417	0.472	0.555	0.547	0.363	0.430	0.200	0.071	0.141
10	0.122	0.049	0.174	0.373	0.341	0.503	0.489	0.368	0.317	0.333	0.387	0.143	0.334	0.143	0.369	0.333	0.355	0.397	0.481	0.460	0.307	0.360	0.165	0.061	0.122
11	0.106	0.043	0.146	0.327	0.289	0.435	0.418	0.309	0.265	0.283	0.334	0.120	0.303	0.121	0.320	0.291	0.302	0.339	0.411	0.391	0.256	0.306	0.137	0.053	0.106
12	0.091	0.037	0.124	0.287	0.239	0.378	0.357	0.268	0.231	0.242	0.292	0.102	0.276	0.103	0.280	0.255	0.250	0.292	0.352	0.342	0.223	0.262	0.116	0.048	0.091
13	0.079	0.033	0.109	0.253	0.201	0.330	0.311	0.233	0.200	0.209	0.258	0.087	0.253	0.089	0.249	0.225	0.210	0.253	0.306	0.299	0.194	0.227	0.099	0.044	0.079
14	0.069	0.030	0.096	0.221	0.173	0.291	0.273	0.206	0.173	0.185	0.227	0.075	0.232	0.077	0.223	0.196	0.181	0.221	0.269	0.266	0.167	0.200	0.085	0.040	0.069
15	0.061	0.027	0.086	0.193	0.149	0.255	0.241	0.182	0.149	0.164	0.200	0.065	0.214	0.067	0.201	0.171	0.156	0.193	0.237	0.235	0.144	0.177	0.073	0.036	0.061
16	0.055	0.025	0.076	0.172	0.132	0.226	0.218	0.160	0.133	0.146	0.179	0.057	0.200	0.059	0.181	0.152	0.139	0.170	0.214	0.208	0.129	0.159	0.065	0.034	0.055
17	0.051	0.023	0.067	0.151	0.119	0.204	0.197	0.141	0.118	0.131	0.160	0.051	0.188	0.053	0.161	0.134	0.125	0.153	0.194	0.184	0.114	0.142	0.057	0.031	0.051
18	0.048	0.021	0.059	0.134	0.108	0.186	0.180	0.125	0.105	0.119	0.144	0.045	0.177	0.048	0.144	0.118	0.113	0.139	0.177	0.163	0.101	0.129	0.051	0.029	0.048
19	0.045	0.020	0.053	0.119	0.098	0.170	0.165	0.112	0.094	0.109	0.131	0.041	0.167	0.043	0.130	0.105	0.103	0.127	0.161	0.146	0.091	0.117	0.046	0.026	0.045
20	0.042	0.018	0.047	0.107	0.089	0.155	0.151	0.101	0.086	0.098	0.118	0.037	0.157	0.039	0.117	0.094	0.093	0.115	0.147	0.132	0.083	0.106	0.041	0.024	0.042

Table B7: No. 36 Mills grenade results: $P_{c\ unarmoured}$

$UF_{casualty}$ / 1 for No. 36 Mills Grenade																									
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.027	0.022	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.027	0.027
3	0.051	0.071	0.059	0.013	0.022	0.002	0.002	0.011	0.022	0.018	0.016	0.064	0.054	0.035	0.017	0.017	0.015	0.006	0.002	0.005	0.029	0.013	0.077	0.099	0.051
4	0.046	0.093	0.085	0.042	0.065	0.021	0.019	0.048	0.064	0.050	0.048	0.143	0.045	0.128	0.054	0.049	0.052	0.034	0.023	0.036	0.072	0.041	0.100	0.088	0.046
5	0.065	0.048	0.099	0.089	0.133	0.073	0.068	0.123	0.118	0.104	0.086	0.163	0.046	0.150	0.090	0.105	0.110	0.096	0.075	0.112	0.136	0.092	0.104	0.048	0.065
6	0.065	0.011	0.088	0.104	0.132	0.131	0.092	0.142	0.128	0.109	0.099	0.109	0.038	0.088	0.099	0.114	0.113	0.138	0.099	0.149	0.145	0.102	0.088	0.019	0.065
7	0.047	0.007	0.075	0.105	0.119	0.140	0.109	0.151	0.125	0.111	0.097	0.071	0.031	0.071	0.099	0.111	0.106	0.138	0.117	0.170	0.136	0.108	0.075	0.007	0.047
8	0.033	0.006	0.071	0.103	0.122	0.136	0.124	0.149	0.121	0.110	0.102	0.062	0.042	0.063	0.107	0.105	0.117	0.123	0.127	0.180	0.121	0.111	0.066	0.007	0.033
9	0.027	0.005	0.059	0.092	0.120	0.130	0.121	0.137	0.105	0.101	0.095	0.053	0.041	0.053	0.098	0.094	0.117	0.109	0.123	0.172	0.105	0.103	0.054	0.006	0.027
10	0.025	0.004	0.047	0.087	0.105	0.123	0.116	0.112	0.095	0.088	0.091	0.045	0.039	0.046	0.087	0.088	0.103	0.099	0.118	0.144	0.094	0.091	0.047	0.005	0.025
11	0.022	0.006	0.040	0.089	0.093	0.116	0.111	0.093	0.085	0.079	0.086	0.039	0.039	0.040	0.081	0.085	0.092	0.091	0.113	0.121	0.084	0.085	0.042	0.008	0.022
12	0.019	0.006	0.035	0.081	0.075	0.100	0.101	0.082	0.081	0.070	0.077	0.033	0.037	0.034	0.075	0.077	0.074	0.077	0.102	0.108	0.080	0.076	0.035	0.008	0.019
13	0.017	0.006	0.032	0.074	0.062	0.091	0.089	0.074	0.073	0.063	0.070	0.028	0.034	0.030	0.071	0.070	0.061	0.069	0.089	0.099	0.073	0.068	0.030	0.008	0.017
14	0.013	0.007	0.030	0.069	0.052	0.082	0.077	0.069	0.063	0.059	0.065	0.024	0.033	0.025	0.067	0.064	0.053	0.063	0.078	0.091	0.061	0.064	0.028	0.009	0.013
15	0.011	0.007	0.028	0.060	0.046	0.074	0.066	0.062	0.053	0.054	0.058	0.021	0.030	0.022	0.062	0.055	0.047	0.056	0.067	0.081	0.051	0.059	0.024	0.009	0.011
16	0.010	0.007	0.025	0.055	0.042	0.065	0.061	0.053	0.047	0.049	0.054	0.018	0.028	0.020	0.058	0.050	0.043	0.049	0.061	0.071	0.046	0.054	0.022	0.009	0.010
17	0.009	0.007	0.023	0.050	0.039	0.058	0.055	0.047	0.042	0.044	0.051	0.016	0.026	0.018	0.053	0.045	0.041	0.045	0.055	0.061	0.041	0.049	0.020	0.009	0.009
18	0.008	0.007	0.020	0.044	0.037	0.052	0.050	0.039	0.038	0.040	0.047	0.015	0.024	0.016	0.048	0.039	0.038	0.040	0.050	0.052	0.036	0.045	0.019	0.008	0.008
19	0.007	0.007	0.019	0.040	0.034	0.047	0.046	0.035	0.034	0.037	0.044	0.013	0.023	0.014	0.044	0.036	0.036	0.036	0.046	0.046	0.033	0.041	0.018	0.008	0.007
20	0.007	0.006	0.017	0.037	0.031	0.043	0.042	0.031	0.031	0.033	0.040	0.012	0.022	0.013	0.040	0.032	0.033	0.032	0.042	0.041	0.030	0.037	0.016	0.007	0.007

Table B8: No. 36 Mills grenade results: $UF_{casualty}$

$UF_{serious}$ / 1 for No. 36 Mills Grenade																									
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.002
2	0.088	0.082	0.029	0.021	0.024	0.003	0.002	0.010	0.020	0.021	0.019	0.024	0.022	0.019	0.019	0.020	0.014	0.004	0.003	0.009	0.033	0.012	0.046	0.085	0.088
3	0.050	0.079	0.113	0.061	0.104	0.055	0.036	0.072	0.096	0.080	0.070	0.147	0.088	0.109	0.070	0.074	0.072	0.052	0.048	0.083	0.117	0.055	0.128	0.097	0.050
4	0.043	0.069	0.091	0.087	0.134	0.131	0.088	0.122	0.131	0.107	0.098	0.157	0.049	0.155	0.101	0.098	0.109	0.103	0.105	0.153	0.139	0.088	0.103	0.062	0.043
5	0.053	0.031	0.080	0.115	0.163	0.185	0.147	0.168	0.147	0.138	0.110	0.121	0.043	0.119	0.110	0.128	0.140	0.151	0.165	0.210	0.159	0.124	0.082	0.029	0.053
6	0.047	0.009	0.063	0.108	0.129	0.210	0.135	0.145	0.126	0.115	0.099	0.074	0.035	0.061	0.096	0.112	0.115	0.163	0.149	0.185	0.133	0.111	0.062	0.014	0.047
7	0.030	0.006	0.050	0.095	0.097	0.177	0.118	0.130	0.105	0.100	0.085	0.046	0.029	0.046	0.082	0.093	0.091	0.138	0.129	0.165	0.106	0.101	0.049	0.007	0.030
8	0.019	0.005	0.045	0.083	0.092	0.135	0.115	0.110	0.090	0.087	0.078	0.038	0.038	0.038	0.079	0.078	0.092	0.105	0.118	0.140	0.084	0.093	0.041	0.006	0.019
9	0.014	0.005	0.035	0.069	0.082	0.106	0.098	0.091	0.071	0.073	0.066	0.031	0.035	0.031	0.065	0.063	0.083	0.081	0.100	0.114	0.066	0.079	0.032	0.005	0.014
10	0.012	0.004	0.027	0.061	0.065	0.092	0.081	0.071	0.058	0.058	0.058	0.025	0.032	0.026	0.053	0.055	0.066	0.070	0.082	0.087	0.053	0.066	0.027	0.005	0.012
11	0.010	0.005	0.022	0.058	0.053	0.076	0.068	0.054	0.047	0.047	0.050	0.020	0.032	0.021	0.045	0.049	0.054	0.058	0.069	0.066	0.043	0.056	0.023	0.006	0.010
12	0.008	0.005	0.018	0.048	0.036	0.052	0.051	0.041	0.040	0.036	0.038	0.015	0.029	0.016	0.036	0.038	0.038	0.043	0.052	0.048	0.035	0.045	0.017	0.006	0.008
13	0.007	0.004	0.013	0.037	0.021	0.028	0.033	0.029	0.027	0.023	0.025	0.011	0.027	0.011	0.024	0.028	0.023	0.028	0.033	0.029	0.023	0.035	0.013	0.005	0.007
14	0.006	0.005	0.013	0.034	0.017	0.024	0.028	0.027	0.022	0.020	0.022	0.009	0.026	0.009	0.022	0.025	0.020	0.026	0.027	0.026	0.019	0.032	0.012	0.005	0.006
15	0.006	0.004	0.012	0.029	0.015	0.021	0.023	0.023	0.018	0.018	0.020	0.008	0.023	0.008	0.020	0.021	0.017	0.022	0.022	0.022	0.016	0.028	0.010	0.005	0.006
16	0.006	0.004	0.011	0.025	0.013	0.018	0.021	0.020	0.016	0.016	0.018	0.007	0.022	0.007	0.018	0.018	0.015	0.019	0.020	0.019	0.014	0.025	0.010	0.005	0.006
17	0.006	0.004	0.010	0.023	0.012	0.015	0.019	0.017	0.013	0.014	0.017	0.006	0.020	0.006	0.017	0.016	0.014	0.017	0.018	0.015	0.012	0.023	0.009	0.005	0.006
18	0.005	0.004	0.009	0.020	0.011	0.013	0.016	0.014	0.011	0.013	0.015	0.005	0.018	0.006	0.015	0.014	0.013	0.015	0.016	0.013	0.010	0.020	0.008	0.004	0.005
19	0.005	0.004	0.008	0.018	0.010	0.012	0.015	0.012	0.010	0.012	0.014	0.005	0.017	0.005	0.013	0.012	0.012	0.013	0.014	0.011	0.009	0.018	0.008	0.004	0.005
20	0.004	0.003	0.007	0.016	0.009	0.010	0.013	0.011	0.009	0.010	0.012	0.005	0.017	0.005	0.012	0.011	0.011	0.012	0.012	0.009	0.008	0.016	0.007	0.004	0.004

Table B9: No. 36 Mills grenade results: $UF_{serious}$

UF_{lethal} / 1 for No. 36 Mills Grenade																									
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.331	0.318	0.312	0.357	0.368	0.337	0.305	0.306	0.315	0.322	0.320	0.312	0.307	0.322	0.323	0.328	0.305	0.282	0.298	0.361	0.387	0.343	0.301	0.337	0.331
2	0.116	0.127	0.189	0.166	0.186	0.254	0.206	0.227	0.193	0.173	0.165	0.163	0.186	0.153	0.168	0.195	0.181	0.204	0.226	0.282	0.197	0.158	0.182	0.133	0.116
3	0.035	0.053	0.094	0.120	0.109	0.163	0.145	0.147	0.128	0.109	0.092	0.119	0.090	0.124	0.094	0.110	0.128	0.142	0.165	0.162	0.109	0.102	0.097	0.053	0.035
4	0.018	0.027	0.041	0.089	0.072	0.110	0.097	0.107	0.088	0.077	0.064	0.072	0.036	0.067	0.060	0.077	0.087	0.100	0.110	0.112	0.072	0.088	0.050	0.028	0.018
5	0.020	0.013	0.025	0.065	0.050	0.075	0.068	0.073	0.063	0.055	0.043	0.034	0.024	0.035	0.041	0.054	0.059	0.070	0.075	0.076	0.050	0.067	0.026	0.013	0.020
6	0.018	0.005	0.019	0.048	0.034	0.058	0.051	0.054	0.043	0.039	0.032	0.019	0.019	0.015	0.032	0.039	0.041	0.054	0.056	0.055	0.034	0.050	0.019	0.007	0.018
7	0.012	0.004	0.014	0.038	0.023	0.047	0.037	0.042	0.033	0.030	0.025	0.010	0.015	0.010	0.024	0.029	0.029	0.045	0.043	0.041	0.025	0.039	0.014	0.004	0.012
8	0.005	0.003	0.012	0.031	0.018	0.031	0.027	0.034	0.024	0.023	0.021	0.008	0.014	0.008	0.020	0.023	0.023	0.030	0.030	0.033	0.018	0.030	0.012	0.003	0.005
9	0.003	0.002	0.009	0.023	0.015	0.020	0.022	0.029	0.019	0.018	0.016	0.006	0.013	0.006	0.016	0.016	0.019	0.020	0.024	0.026	0.014	0.025	0.009	0.003	0.003
10	0.003	0.003	0.007	0.019	0.013	0.015	0.018	0.020	0.014	0.014	0.014	0.005	0.011	0.005	0.014	0.013	0.016	0.015	0.020	0.018	0.011	0.020	0.007	0.002	0.003
11	0.002	0.002	0.006	0.017	0.010	0.012	0.015	0.014	0.012	0.011	0.011	0.004	0.011	0.004	0.011	0.011	0.012	0.012	0.016	0.013	0.008	0.015	0.006	0.002	0.002
12	0.002	0.002	0.005	0.014	0.006	0.009	0.012	0.010	0.011	0.008	0.009	0.003	0.010	0.003	0.009	0.009	0.008	0.009	0.014	0.009	0.008	0.013	0.005	0.002	0.002
13	0.002	0.002	0.004	0.012	0.005	0.006	0.009	0.009	0.009	0.007	0.008	0.002	0.009	0.002	0.008	0.007	0.006	0.008	0.011	0.007	0.006	0.011	0.004	0.002	0.002
14	0.002	0.002	0.004	0.010	0.004	0.006	0.008	0.007	0.007	0.006	0.007	0.002	0.008	0.002	0.007	0.006	0.005	0.007	0.008	0.006	0.004	0.009	0.004	0.001	0.002
15	0.001	0.002	0.004	0.007	0.003	0.005	0.006	0.007	0.005	0.005	0.006	0.002	0.007	0.002	0.006	0.005	0.003	0.005	0.007	0.005	0.003	0.009	0.003	0.001	0.001
16	0.002	0.002	0.003	0.007	0.002	0.003	0.004	0.006	0.005	0.004	0.005	0.002	0.007	0.001	0.006	0.004	0.003	0.005	0.005	0.004	0.003	0.007	0.003	0.001	0.002
17	0.002	0.001	0.002	0.005	0.002	0.003	0.004	0.004	0.004	0.003	0.004	0.002	0.006	0.001	0.005	0.004	0.003	0.004	0.005	0.003	0.003	0.006	0.002	0.001	0.002
18	0.002	0.001	0.002	0.005	0.002	0.002	0.004	0.003	0.003	0.003	0.004	0.001	0.005	0.001	0.004	0.003	0.002	0.003	0.004	0.003	0.002	0.005	0.002	0.001	0.002
19	0.001	0.001	0.002	0.004	0.002	0.002	0.003	0.002	0.003	0.003	0.004	0.001	0.005	0.001	0.004	0.002	0.002	0.003	0.003	0.002	0.002	0.004	0.002	0.001	0.001
20	0.001	0.001	0.002	0.003	0.002	0.001	0.002	0.002	0.002	0.003	0.003	0.001	0.004	0.001	0.003	0.002	0.001	0.002	0.002	0.002	0.001	0.003	0.002	0.001	0.001

Table B10: No. 36 Mills grenade results: UF_{lethal}

r / m	**$Pc_{unarmoured}$ / 1 for 105mm Shell**																								
	Approach angle (yaw), ϑ / °																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2.5	1.000	1.000	0.989	0.998	0.885	1.000	1.000	0.999	0.996	0.999	0.390	0.797	0.857	0.724	0.481	1.000	1.000	1.000	1.000	1.000	0.913	0.996	0.982	1.000	1.000
5	1.000	0.963	0.551	0.592	0.415	0.999	1.000	0.853	0.747	0.850	0.091	0.533	0.545	0.486	0.053	0.919	0.855	0.888	1.000	0.989	0.477	0.651	0.610	0.957	1.000
7.5	0.999	0.734	0.319	0.348	0.225	0.958	0.970	0.580	0.417	0.558	0.058	0.333	0.356	0.340	0.028	0.662	0.564	0.652	0.990	0.870	0.251	0.395	0.389	0.752	0.999
10	0.995	0.546	0.213	0.232	0.144	0.781	0.866	0.378	0.258	0.338	0.038	0.204	0.267	0.215	0.022	0.449	0.379	0.407	0.924	0.665	0.156	0.248	0.254	0.566	0.995
12.5	0.981	0.409	0.152	0.165	0.090	0.609	0.718	0.256	0.174	0.215	0.028	0.131	0.208	0.143	0.017	0.324	0.239	0.279	0.778	0.488	0.103	0.166	0.182	0.428	0.981
15	0.954	0.310	0.115	0.116	0.061	0.462	0.569	0.187	0.109	0.155	0.021	0.086	0.166	0.098	0.013	0.232	0.161	0.198	0.648	0.374	0.073	0.120	0.133	0.328	0.954
17.5	0.922	0.246	0.087	0.085	0.046	0.368	0.467	0.137	0.079	0.116	0.016	0.061	0.141	0.073	0.010	0.168	0.119	0.150	0.550	0.278	0.054	0.091	0.101	0.261	0.922
20	0.886	0.201	0.068	0.064	0.037	0.305	0.384	0.104	0.062	0.089	0.012	0.046	0.120	0.057	0.008	0.126	0.093	0.119	0.468	0.213	0.041	0.072	0.078	0.212	0.886
22.5	0.846	0.165	0.054	0.050	0.029	0.256	0.320	0.084	0.051	0.070	0.010	0.036	0.105	0.045	0.006	0.098	0.073	0.097	0.401	0.172	0.032	0.058	0.062	0.173	0.846
25	0.814	0.137	0.043	0.040	0.023	0.224	0.275	0.071	0.042	0.056	0.008	0.029	0.094	0.036	0.005	0.077	0.057	0.082	0.354	0.144	0.025	0.048	0.049	0.142	0.814
27.5	0.782	0.113	0.035	0.033	0.019	0.196	0.241	0.061	0.034	0.045	0.006	0.023	0.086	0.029	0.004	0.062	0.046	0.071	0.313	0.125	0.020	0.040	0.040	0.117	0.782
30	0.751	0.095	0.029	0.028	0.015	0.172	0.213	0.053	0.028	0.037	0.005	0.019	0.079	0.024	0.004	0.051	0.037	0.062	0.278	0.110	0.016	0.034	0.033	0.098	0.751
32.5	0.717	0.080	0.024	0.024	0.013	0.150	0.189	0.046	0.023	0.031	0.004	0.016	0.072	0.020	0.003	0.042	0.032	0.054	0.245	0.097	0.014	0.029	0.028	0.083	0.717
35	0.685	0.069	0.021	0.021	0.011	0.129	0.167	0.040	0.020	0.026	0.004	0.013	0.066	0.017	0.003	0.037	0.028	0.046	0.213	0.086	0.012	0.025	0.024	0.072	0.685
37.5	0.651	0.060	0.018	0.018	0.010	0.111	0.150	0.036	0.017	0.023	0.003	0.012	0.060	0.015	0.002	0.032	0.025	0.040	0.187	0.078	0.011	0.021	0.021	0.063	0.651
40	0.613	0.053	0.016	0.016	0.008	0.097	0.132	0.031	0.015	0.020	0.003	0.010	0.054	0.013	0.002	0.028	0.022	0.035	0.164	0.068	0.010	0.019	0.019	0.055	0.613
42.5	0.578	0.047	0.014	0.014	0.007	0.085	0.118	0.027	0.013	0.018	0.003	0.009	0.049	0.011	0.002	0.025	0.020	0.031	0.145	0.061	0.009	0.016	0.017	0.049	0.578
45	0.546	0.042	0.012	0.013	0.007	0.075	0.104	0.024	0.012	0.016	0.002	0.008	0.045	0.010	0.002	0.022	0.018	0.027	0.129	0.054	0.008	0.015	0.015	0.044	0.546
47.5	0.522	0.037	0.011	0.011	0.006	0.066	0.093	0.021	0.011	0.014	0.002	0.007	0.043	0.009	0.001	0.020	0.017	0.024	0.114	0.048	0.007	0.013	0.014	0.039	0.522
50	0.504	0.033	0.010	0.010	0.006	0.058	0.082	0.019	0.010	0.013	0.002	0.006	0.041	0.008	0.001	0.018	0.016	0.021	0.100	0.043	0.007	0.011	0.013	0.035	0.504

Table B11: 105mm shell results: $P_{c\ unarmoured}$

	$UF_{casualty}$ / 1 for 105mm Shell																								
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.5	0.000	0.000	0.101	0.016	0.035	0.000	0.000	0.000	0.004	0.009	0.317	0.651	0.476	0.559	0.418	0.005	0.001	0.000	0.000	0.000	0.048	0.032	0.107	0.000	0.000
5	0.000	0.056	0.087	0.114	0.028	0.001	0.000	0.026	0.057	0.099	0.008	0.089	0.080	0.092	0.000	0.054	0.031	0.020	0.000	0.012	0.030	0.100	0.079	0.066	0.000
7.5	0.000	0.124	0.063	0.089	0.026	0.020	0.011	0.045	0.048	0.146	0.006	0.102	0.047	0.103	0.001	0.113	0.030	0.034	0.003	0.059	0.026	0.097	0.056	0.117	0.000
10	0.003	0.125	0.054	0.071	0.029	0.041	0.039	0.033	0.054	0.113	0.007	0.072	0.041	0.073	0.005	0.102	0.053	0.020	0.023	0.073	0.025	0.070	0.056	0.120	0.003
12.5	0.008	0.107	0.045	0.056	0.019	0.051	0.046	0.028	0.041	0.086	0.007	0.048	0.034	0.050	0.006	0.095	0.033	0.024	0.034	0.067	0.018	0.050	0.044	0.106	0.008
15	0.017	0.088	0.037	0.039	0.012	0.043	0.049	0.028	0.024	0.068	0.006	0.032	0.026	0.034	0.005	0.070	0.021	0.026	0.042	0.056	0.013	0.038	0.034	0.087	0.017
17.5	0.020	0.074	0.030	0.029	0.010	0.045	0.047	0.019	0.017	0.053	0.005	0.023	0.021	0.026	0.004	0.052	0.017	0.019	0.043	0.052	0.010	0.029	0.028	0.075	0.020
20	0.024	0.064	0.024	0.023	0.009	0.037	0.042	0.020	0.014	0.041	0.004	0.018	0.018	0.020	0.003	0.040	0.015	0.020	0.039	0.040	0.008	0.023	0.022	0.064	0.024
22.5	0.028	0.055	0.021	0.018	0.010	0.033	0.036	0.016	0.012	0.032	0.003	0.015	0.017	0.016	0.003	0.031	0.013	0.017	0.035	0.036	0.009	0.019	0.021	0.055	0.028
25	0.032	0.048	0.016	0.014	0.008	0.030	0.034	0.014	0.011	0.025	0.002	0.012	0.016	0.013	0.002	0.024	0.010	0.015	0.036	0.031	0.007	0.016	0.017	0.048	0.032
27.5	0.041	0.040	0.013	0.012	0.007	0.030	0.038	0.013	0.008	0.020	0.002	0.009	0.016	0.010	0.002	0.019	0.008	0.014	0.039	0.029	0.006	0.014	0.013	0.040	0.041
30	0.046	0.034	0.011	0.010	0.005	0.028	0.038	0.014	0.006	0.016	0.001	0.008	0.016	0.008	0.002	0.016	0.006	0.015	0.038	0.028	0.005	0.012	0.011	0.033	0.046
32.5	0.050	0.029	0.009	0.009	0.004	0.030	0.035	0.013	0.005	0.013	0.001	0.006	0.015	0.007	0.001	0.013	0.005	0.014	0.036	0.028	0.004	0.010	0.009	0.028	0.050
35	0.056	0.025	0.007	0.008	0.003	0.027	0.033	0.012	0.004	0.011	0.001	0.005	0.014	0.006	0.001	0.011	0.004	0.012	0.033	0.026	0.003	0.009	0.007	0.025	0.056
37.5	0.058	0.021	0.006	0.007	0.003	0.025	0.034	0.011	0.004	0.009	0.001	0.005	0.013	0.005	0.001	0.010	0.004	0.011	0.031	0.027	0.003	0.007	0.006	0.022	0.058
40	0.058	0.019	0.005	0.006	0.002	0.022	0.030	0.010	0.003	0.008	0.001	0.004	0.011	0.004	0.001	0.008	0.003	0.010	0.028	0.023	0.003	0.007	0.006	0.019	0.058
42.5	0.058	0.017	0.005	0.006	0.002	0.022	0.028	0.009	0.003	0.007	0.001	0.004	0.010	0.004	0.001	0.008	0.003	0.009	0.026	0.022	0.002	0.006	0.005	0.017	0.058
45	0.058	0.015	0.004	0.005	0.002	0.020	0.026	0.008	0.003	0.006	0.001	0.003	0.010	0.003	0.001	0.007	0.003	0.008	0.026	0.022	0.002	0.005	0.004	0.015	0.058
47.5	0.058	0.013	0.004	0.004	0.002	0.017	0.027	0.007	0.002	0.006	0.001	0.003	0.010	0.003	0.000	0.006	0.003	0.007	0.025	0.020	0.002	0.005	0.004	0.014	0.058
50	0.064	0.012	0.003	0.004	0.002	0.015	0.024	0.006	0.003	0.005	0.001	0.002	0.010	0.003	0.000	0.005	0.003	0.006	0.022	0.018	0.002	0.004	0.004	0.012	0.064

Table B12: 105mm shell results: $UF_{casualty}$

$UF_{serious}$ / 1 for 105mm Shell																									
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.5	0.000	0.018	0.192	0.029	0.045	0.000	0.000	0.001	0.008	0.014	0.208	0.538	0.496	0.443	0.294	0.009	0.002	0.000	0.000	0.000	0.059	0.054	0.198	0.020	0.000
5	0.000	0.127	0.082	0.107	0.029	0.003	0.001	0.034	0.062	0.121	0.007	0.087	0.084	0.085	0.000	0.071	0.037	0.026	0.000	0.017	0.031	0.098	0.077	0.146	0.000
7.5	0.001	0.143	0.052	0.071	0.024	0.025	0.014	0.046	0.056	0.144	0.005	0.084	0.042	0.085	0.001	0.114	0.040	0.037	0.004	0.066	0.027	0.079	0.048	0.139	0.001
10	0.005	0.115	0.042	0.052	0.025	0.042	0.042	0.034	0.043	0.104	0.005	0.056	0.033	0.057	0.003	0.096	0.045	0.025	0.026	0.068	0.022	0.052	0.044	0.113	0.005
12.5	0.013	0.085	0.034	0.039	0.016	0.051	0.046	0.028	0.031	0.076	0.005	0.035	0.006	0.037	0.003	0.086	0.027	0.025	0.035	0.061	0.016	0.035	0.034	0.086	0.013
15	0.022	0.064	0.028	0.027	0.010	0.041	0.044	0.023	0.017	0.059	0.004	0.023	0.002	0.024	0.003	0.061	0.017	0.022	0.041	0.050	0.011	0.025	0.025	0.065	0.022
17.5	0.025	0.051	0.022	0.019	0.008	0.039	0.041	0.017	0.012	0.044	0.003	0.016	0.000	0.018	0.002	0.045	0.014	0.017	0.039	0.043	0.009	0.018	0.020	0.053	0.025
20	0.028	0.041	0.017	0.014	0.007	0.032	0.036	0.015	0.010	0.034	0.002	0.012	0.000	0.013	0.002	0.034	0.012	0.016	0.035	0.032	0.007	0.014	0.016	0.042	0.028
22.5	0.031	0.033	0.014	0.010	0.008	0.028	0.031	0.012	0.008	0.025	0.002	0.009	0.000	0.010	0.001	0.026	0.010	0.013	0.031	0.028	0.007	0.011	0.015	0.034	0.031
25	0.034	0.027	0.011	0.008	0.006	0.025	0.028	0.010	0.007	0.019	0.001	0.007	0.000	0.007	0.001	0.019	0.008	0.011	0.031	0.024	0.006	0.009	0.011	0.028	0.034
27.5	0.043	0.022	0.008	0.006	0.005	0.025	0.031	0.010	0.005	0.015	0.001	0.005	0.000	0.005	0.001	0.014	0.005	0.011	0.033	0.023	0.005	0.007	0.009	0.022	0.043
30	0.047	0.017	0.007	0.005	0.004	0.023	0.031	0.010	0.004	0.011	0.001	0.004	0.000	0.004	0.001	0.011	0.004	0.011	0.032	0.022	0.004	0.006	0.007	0.017	0.047
32.5	0.049	0.013	0.005	0.004	0.003	0.024	0.028	0.009	0.003	0.009	0.000	0.004	0.000	0.004	0.001	0.009	0.003	0.010	0.029	0.021	0.003	0.005	0.005	0.014	0.049
35	0.054	0.010	0.004	0.003	0.003	0.021	0.025	0.008	0.003	0.007	0.000	0.003	0.000	0.003	0.001	0.008	0.003	0.009	0.027	0.019	0.003	0.003	0.004	0.011	0.054
37.5	0.054	0.005	0.003	0.002	0.002	0.019	0.026	0.007	0.002	0.006	0.000	0.002	0.000	0.002	0.001	0.006	0.002	0.008	0.024	0.019	0.002	0.003	0.003	0.006	0.054
40	0.051	0.004	0.003	0.002	0.002	0.016	0.023	0.006	0.002	0.005	0.000	0.002	0.000	0.002	0.000	0.006	0.002	0.007	0.022	0.017	0.002	0.002	0.003	0.003	0.051
42.5	0.049	0.003	0.002	0.002	0.002	0.015	0.021	0.005	0.002	0.005	0.000	0.002	0.000	0.002	0.000	0.005	0.002	0.006	0.021	0.015	0.002	0.002	0.002	0.003	0.049
45	0.048	0.003	0.002	0.001	0.001	0.014	0.020	0.005	0.001	0.004	0.000	0.002	0.000	0.002	0.000	0.004	0.001	0.005	0.020	0.015	0.001	0.002	0.002	0.003	0.048
47.5	0.047	0.002	0.002	0.001	0.001	0.012	0.019	0.004	0.001	0.004	0.000	0.001	0.000	0.001	0.000	0.004	0.001	0.004	0.017	0.013	0.001	0.001	0.002	0.002	0.047
50	0.052	0.002	0.001	0.001	0.001	0.010	0.017	0.003	0.001	0.003	0.000	0.001	0.000	0.001	0.000	0.004	0.001	0.003	0.015	0.012	0.001	0.001	0.002	0.002	0.052

Table B13: 105mm shell results: $UF_{serious}$

	***UF**$_{lethal}$* **/ 1 for 105mm Shell**																								
***r* / m**	**Approach angle (yaw), ϑ / º**																								
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.5	0.351	0.289	0.269	0.154	0.094	0.001	0.001	0.068	0.097	0.313	0.048	0.083	0.171	0.041	0.068	0.292	0.057	0.066	0.000	0.011	0.113	0.131	0.266	0.304	0.351
5	0.146	0.186	0.040	0.041	0.029	0.068	0.062	0.068	0.084	0.253	0.002	0.048	0.042	0.045	0.000	0.224	0.071	0.062	0.025	0.148	0.030	0.044	0.045	0.187	0.146
7.5	0.126	0.068	0.021	0.023	0.018	0.089	0.079	0.044	0.043	0.147	0.000	0.045	0.014	0.047	0.000	0.142	0.037	0.042	0.050	0.125	0.021	0.024	0.022	0.066	0.126
10	0.114	0.040	0.016	0.016	0.017	0.054	0.091	0.028	0.027	0.084	0.001	0.028	0.009	0.029	0.001	0.082	0.028	0.021	0.076	0.075	0.013	0.015	0.016	0.039	0.114
12.5	0.114	0.025	0.012	0.012	0.010	0.048	0.061	0.018	0.018	0.051	0.001	0.017	0.003	0.018	0.001	0.060	0.015	0.016	0.052	0.052	0.010	0.009	0.011	0.025	0.114
15	0.091	0.017	0.010	0.007	0.006	0.032	0.044	0.013	0.010	0.039	0.001	0.011	0.001	0.011	0.001	0.039	0.008	0.011	0.042	0.039	0.007	0.006	0.008	0.017	0.091
17.5	0.070	0.011	0.007	0.005	0.005	0.024	0.034	0.009	0.006	0.028	0.001	0.007	0.000	0.008	0.001	0.027	0.007	0.009	0.035	0.029	0.005	0.004	0.006	0.011	0.070
20	0.056	0.008	0.005	0.004	0.005	0.019	0.027	0.007	0.005	0.021	0.000	0.005	0.000	0.005	0.000	0.019	0.006	0.007	0.027	0.020	0.004	0.002	0.005	0.008	0.056
22.5	0.049	0.006	0.005	0.003	0.004	0.015	0.022	0.005	0.004	0.016	0.000	0.004	0.000	0.004	0.000	0.014	0.005	0.005	0.023	0.017	0.004	0.002	0.004	0.005	0.049
25	0.046	0.004	0.004	0.002	0.003	0.013	0.019	0.004	0.003	0.012	0.000	0.004	0.000	0.003	0.000	0.011	0.003	0.004	0.020	0.014	0.003	0.001	0.003	0.004	0.046
27.5	0.055	0.003	0.003	0.001	0.002	0.013	0.020	0.004	0.003	0.010	0.000	0.003	0.000	0.003	0.000	0.008	0.002	0.004	0.020	0.013	0.002	0.001	0.002	0.003	0.055
30	0.056	0.003	0.002	0.001	0.002	0.012	0.018	0.003	0.002	0.008	0.000	0.002	0.000	0.002	0.000	0.006	0.002	0.004	0.019	0.012	0.002	0.001	0.001	0.002	0.056
32.5	0.054	0.002	0.002	0.001	0.002	0.011	0.016	0.003	0.002	0.006	0.000	0.002	0.000	0.002	0.000	0.005	0.002	0.003	0.018	0.011	0.001	0.001	0.001	0.001	0.054
35	0.058	0.002	0.001	0.001	0.001	0.010	0.015	0.003	0.001	0.005	0.000	0.001	0.000	0.001	0.000	0.004	0.001	0.003	0.016	0.011	0.001	0.001	0.001	0.001	0.058
37.5	0.056	0.001	0.001	0.001	0.001	0.009	0.016	0.003	0.001	0.004	0.000	0.001	0.000	0.001	0.000	0.003	0.001	0.002	0.014	0.011	0.001	0.001	0.001	0.001	0.056
40	0.050	0.001	0.001	0.000	0.001	0.008	0.014	0.002	0.001	0.003	0.000	0.001	0.000	0.001	0.000	0.003	0.001	0.002	0.013	0.009	0.001	0.000	0.001	0.001	0.050
42.5	0.048	0.001	0.001	0.000	0.001	0.007	0.013	0.002	0.001	0.003	0.000	0.001	0.000	0.001	0.000	0.003	0.001	0.002	0.012	0.008	0.001	0.000	0.001	0.001	0.048
45	0.044	0.000	0.001	0.000	0.001	0.007	0.012	0.002	0.001	0.003	0.000	0.001	0.000	0.001	0.000	0.002	0.001	0.002	0.011	0.009	0.001	0.000	0.001	0.001	0.044
47.5	0.042	0.000	0.001	0.000	0.001	0.006	0.012	0.001	0.001	0.002	0.000	0.001	0.000	0.001	0.000	0.002	0.001	0.001	0.010	0.008	0.001	0.000	0.001	0.000	0.042
50	0.043	0.000	0.000	0.000	0.001	0.005	0.010	0.001	0.001	0.002	0.000	0.001	0.000	0.001	0.000	0.002	0.001	0.001	0.009	0.007	0.001	0.000	0.000	0.000	0.043

Table B14: 105mm shell results: *UF*$_{lethal}$

B.3 GRAPHICAL OUTPUT (MATLAB® M-FILES)

```
%---------------------------------------------------------------
%Written by C Couldrick and Dr E Hughes, Cranfield University.
%Filename is in.m .
%Converts the matrix from Excel (”out”) and generates polar
%coordinates or range, r and angle, theta.

%Approach angles or threat azimuth in radians.  Range in metres.
      ang=out(1,2:26)/180*pi;
      r=out(2:22,1);

%Pc for the unprotected man and UF values for casualty, serious and
%lethal incapacitation criteria.
      pc=out(2:22,2:26);
      cas=out(23:43,2:26);
      ser=out(44:64,2:26);
      let=out(65:85,2:26);

%Define the Cartesian grid.
      [x,y]=meshgrid(ang,r);

%Convert to polar coordinates.
      [X,Y]=pol2cart(x,y)
%---------------------------------------------------------------
%Written by C Couldrick and Dr E Hughes, Cranfield University.
%Filename is prepXX.m , where XX is the maximum range in metres.
%Generates a polar axis for the maximum range XX.

      h=polar([0 2*pi],[0 XX]);
      delete(h);
      hold on

%The relevant graph is then generated by entering the following:
%     contourf(X,Y,S,10);
%     colorbar;
%where S is the string pc, cas, ser or let as appropriate.
%---------------------------------------------------------------
```

APPENDIX C: MUSCULAR COMFORT MODELLING OF A PERSONAL ARMOUR WEARER

C.1 DRAFT PROPOSAL FOR DLO R&PS (FORMERLY DCTA)

CA Couldrick, 14 May 2001

Introduction

One of the most important selection criterion for armour materials is the trade-off between weight-per-unit-area (areal density) and protection (*e.g.* V_{50} for given projectiles). Other mechanical factors such as bulk and flexibility are also significant selection criteria, particularly for large personal armour systems. For example, existing EOD suits are heavy and restrictive, reducing the wearer's capability[1]. It is the goal of armour design to find the optimum balance between ergonomic capability and protection[2]. There are great benefits of understanding this trade-off better, not least for the development of EOD suits.

Protection and ergonomic requirements are not the same for all parts of the body. The head and torso are more vulnerable when attacked than the arms and legs, so need more armour. Casualty reduction analysis software (CASPER) is already used to assess this variation of protection requirements[3]. Ergonomic requirements vary too: *e.g.* elbows and shoulders need more flexibility and less weight than the abdomen. However, these requirements are frequently based on the designers' experience until prototype garments are undergo user trials. It would be beneficial to use ergonomic software in combination with CASPER to assess armour constructions before they are prototyped.

No software exists that can assess the ergonomics of armour fully, *i.e.* including mechanical, thermal and psychological effects. However, biomechanics analysis software[†] is available to model muscular comfort. It enables designs to be produced that minimise the muscular effort needed to complete a task[4]. This software is being used by the French to assess rifle ergonomics for the FELIN project (equivalent to FIST). Major car manufacturers use it to develop vehicle interiors. PAM-Comfort™ has the potential to model the most important stresses on the wearer.

Optimisation of personal armour ergonomics is becoming increasingly important because significant improvement of ballistic materials is unlikely in the medium-term future. Any major development of armour is likely to come from combining existing materials better[5]. Thus, there is scope to improve the capability of armour through the knowledge gained by using biomechanics software.

Background

This proposal is derived from the author's on-going, doctoral research into "A Systems Approach to Personal Armour Design" at the Royal Military College of Science (RMCS). The original project is sponsored jointly by DCTA[‡] and the Engineering and Physical Sciences Research Council (EPSRC), and will conclude in October 2002.

† PAM-Comfort™ from ESI Software, France.

‡ The sponsor was called the Defence Clothing and Textiles Agency at the start of the author's research in October 1998. Currently, it is DLO R&PS

It is envisaged that collaboration between the author at RMCS, DCTA and ESI Software of France will provide mutual benefits. The work outlined in this proposal can run in tandem with the aforementioned doctoral research and would require additional funding. Initially, the project will aim to prove the potential of biomechanics software for armour design. The model can be developed further based on the success at each project milestone. Ultimately, the goal is to develop a complete muscular comfort model of armour, capable of being used by the garment designer.

PAM-Comfort™

PAM-Comfort™ is a computer-based biomechanical model of the human body that has been developed by ESI Software. It is a natural addition to their existing range of products, which includes human-vehicle crash simulation. PAM-Comfort™ models the skeleton and muscular system of a 50th percentile, European, male human. The skeletal data comes from Viewpoint and the muscles are based on AV Hill's widely accepted[6] model. An algorithm is used to calculate the minimum work[†] required to maintain a static posture. This determines the most comfortable and energy-efficient tools, tasks[‡], etc. For example, the French military (DGA) is using PAM-Comfort™ to assess soldiers' ability to maintain aiming accuracy of a new rifle.

ESI Software has published details of validation and design projects and works with major manufacturers. Nevertheless, PAM-Comfort™ is a 'cutting-edge' program and requires separate development for new areas of interest. An armour model with flexibility, mass and bulk would be constructed for the purposes of this proposal. Thus, collaborative work can benefit both DCTA and ESI Software's product development, and contribute to the authors' research.

Suggestions for Work

It is suggested that the work consists of three phases or sub-projects of increasing magnitude and benefit. The costs and funding of each phase is discussed in the succeeding section of this proposal. This section details the aims and objectives of undertaking each phase.

Phase One

The first phase would model armour on the upper body as a distributed weight, with zero bulk and infinite flexibility. This simulates the most important ergonomic consideration in the history of personal armour: how does changing the weight distribution of armour affect the wearer? It is work that is possible to undertake with PAM-Comfort™ as it is now with minimal risk. The author can complete the work at RMCS in one man-month, after three to five days of training.

† This assumes that the human body will try minimise the energy required to complete a task.

‡ Currently, no models are available that simulate dynamic human actions reliably. Therefore, tasks are constructed from a series of static 'snapshots'.

Phase Two

A small-scale model of armour that includes mass, flexibility and bulk would be developed in phase two. It would be applied to one of the simplest yet useful joints – the elbow. This model of an armour sleeve, such as those of EOD suits, can minimise the project risk while giving an insight into a real application. ESI Software will need to develop the code to include an amour model based upon materials information supplied by DCTA and the author. This is estimated to take two to three man-months of work by ESI Software in France and the author at RMCS. Phase two has high academic value and is a proving ground for the potential benefits of a full-scale model.

N.B. The armour material would be modelled as a single layer with the potential for anisotropic properties.

Phase Three

Phase three would involve the construction of a full-scale human-armour model, depending on the success of phase two. It would develop the small-scale simulation into a valuable commercial tool to assess the mechanical ergonomics of real personal. This phase is estimated as taking nine man-months to complete and offers significant benefits to both DCTA and ESI Software.

Costs and Funding

It is proposed that the cost of each phase is shared between the partners, proportional to the potential benefits.

DCTA and the author gain the benefits of learning in phase one. However, ESI Software is willing[7] to contribute an academic licence for phases one and two. RMCS can provide the Silicon Graphics hardware to run PAM-Comfort™ for phases one and two. DCTA is asked to fund three to five days of training and up to five days of support for phase one. Validation experiments for phases one and two can be carried out as part of the author's doctoral research.

Phases two and three will also provide learning benefits to ESI Software. They have expressed interest[8] in providing half of the man-days for phases two and three. The academic license will continue to be appropriate for phase two but a commercial license would be needed in phases 3. DCTA is asked to fund the other half of the man-days for phases two and three.

The *approximate* costs to DCTA, if no other funding is obtained (see below), are:

Phase One	= £5,000
Phase Two	= £20,000
Phase Three	= £200,000

N.B. There is a scheme run by the MoD and the EPSRC to fund research. This could reduce the costs to DCTA by fifty percent; at least for phases one and two that are more academic.

Timeframe

It is suggested that the project is run at approximately half pace (i.e. one man-month will be completed in a duration of two months). This enables all parties to maintain their existing commitments. Thus, the proposed timeframe for the project is:

Phase One	Two months commencing July 2001
Phase Two	Three months commencing September 2001
Phase Three	Eighteen months commencing January 2002

Conclusion

A biomechanical model, PAM-Comfort™, can be developed to simulate the interaction between armour and the wearer. This can be used in conjunction with the protection assessment from casualty reduction analysis software (*e.g.* CASPER) to increase the capability of armour wearers. Moreover, this can reduce the need to build prototypes. The ergonomics knowledge gained through this approach is increasingly important because ballistic materials have a limited potential for improvement in the medium-term.

All parties involved have strong but defined areas of expertise. Collaborative work is a chance to extend the knowledge and capabilities each other, while sharing the burden. There is a further opportunity to reduce the cost by involving the EPSRC through jointly funded research.

This is a *draft* proposal and is open to negotiation.

References

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APPENDIX D: OPTIMISATION OF PERSONAL ARMOUR FOR PROTECTION

D.1 SIMULATION VARIABLES

No.	Threat	Armour Material Code
1	L2A2 Grenade	A or G
2	L2A2 Grenade	B or H
3	L2A2 Grenade	C or I
4	L2A2 Grenade	D or J
5	L2A2 Grenade	E or K
6	L2A2 Grenade	F or L
7	No. 36 Mills Grenade	A or G
8	No. 36 Mills Grenade	B or H
9	No. 36 Mills Grenade	C or I
10	No. 36 Mills Grenade	D or J
11	No. 36 Mills Grenade	E or K
12	No. 36 Mills Grenade	F or L

Table D1: Simulation variables

D.2 MATERIALS DEFINITION

Material code		**A**	**B**	**C**	**D**	**E**	**F**
Material		a	a	a	a	a	a
V_L / ms^{-1} @ fragment mass, m =	0.13g	725.0	870.0	1015.0	1160.0	1305.0	1450.0
	0.25g	651.5	781.8	912.1	1042.4	1172.7	1303.0
	1.10g	500.0	600.0	700.0	800.0	900.0	1000.0
	4.06g	397.0	476.4	555.8	635.2	714.6	794.0
Relative areal density, ρ_A / m^{-2}		1	1.44	1.96	2.56	3.24	4
Relative cost per unit area $\$_A$ / m^{-2}		1	1.44	1.96	2.56	3.24	4
Material code		**G**	**H**	**I**	**J**	**K**	**L**
Material		b	b	b	b	b	b
V_L / ms^{-1} @ fragment mass, m =	0.13g	725.0	870.0	1015.0	1160.0	1305.0	1450.0
	0.25g	651.5	781.8	912.1	1042.4	1172.7	1303.0
	1.10g	500.0	600.0	700.0	800.0	900.0	1000.0
	4.06g	397.0	476.4	555.8	635.2	714.6	794.0
Relative areal density, ρ_A / m^{-2}		0.90	1.30	1.76	2.30	2.92	3.60
Relative cost per unit area $\$_A$ / m^{-2}		4	5.76	7.84	10.24	12.96	16

Table D2: Theoretical materials' protective, weight and cost properties

D.3 RELATIVE WEIGHTS & COSTS OF ARMOUR SECTIONS

		Relative weight of different armours for each body region / 1												
Incapacitation criterion	**Matrix name**	**Armour level**												
		U	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Thorax	weight	0	0.227	0.327	0.445	0.581	0.735	0.908	0.204	0.294	0.400	0.523	0.662	0.817
Abdomen		0	0.150	0.216	0.293	0.383	0.485	0.599	0.135	0.194	0.264	0.345	0.437	0.539
Pelvis		0	0.192	0.277	0.377	0.492	0.623	0.769	0.173	0.249	0.339	0.443	0.561	0.693
Arms		0	0.459	0.661	0.900	1.176	1.488	1.837	0.413	0.595	0.810	1.058	1.339	1.653
Legs		0	1.001	1.441	1.962	2.562	3.242	4.003	0.901	1.297	1.765	2.306	2.918	3.603

Table D3: Relative weights of armour sections

		Relative cost of different armours for each body region / 1												
Incapacitation criterion	**Matrix name**	**Armour level**												
		U	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Thorax	cost	0	0.227	0.272	0.318	0.363	0.408	0.454	0.908	1.089	1.271	1.452	1.634	1.815
Abdomen		0	0.150	0.180	0.210	0.240	0.270	0.299	0.599	0.719	0.838	0.958	1.078	1.198
Pelvis		0	0.192	0.231	0.269	0.308	0.346	0.385	0.769	0.923	1.077	1.231	1.385	1.539
Arms		0	0.459	0.551	0.643	0.735	0.827	0.919	1.837	2.204	2.572	2.939	3.307	3.674
Legs		0	1.001	1.201	1.401	1.601	1.801	2.002	4.003	4.804	5.604	6.405	7.205	8.006

Table D4: Relative costs of armour sections

D.4 OUTPUT FROM CASPER TRANSFORMED IN EXCEL®

P_i / 1 for L2A2 Grenade														
Incapacitation criterion	**Matrix name**	**Armour level**												
		U	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Serious	pisl2	0.5740	0.5665	0.5616	0.5441	0.5366	0.5249	0.5099	0.5665	0.5616	0.5441	0.5366	0.5249	0.5099
		0.5820	0.5801	0.5791	0.5759	0.5743	0.5718	0.5681	0.5801	0.5791	0.5759	0.5743	0.5718	0.5681
		0.6484	0.6461	0.6445	0.6379	0.6363	0.6336	0.6300	0.6461	0.6445	0.6379	0.6363	0.6336	0.6300
		0.6389	0.6350	0.6328	0.6294	0.6249	0.6181	0.6118	0.6350	0.6328	0.6294	0.6249	0.6181	0.6118
		0.9436	0.9419	0.9410	0.9395	0.9379	0.9354	0.9313	0.9419	0.9410	0.9395	0.9379	0.9354	0.9313
Lethal	pill2	0.2503	0.2391	0.2330	0.2215	0.2129	0.2014	0.1855	0.2391	0.2330	0.2215	0.2129	0.2014	0.1855
		0.0841	0.0798	0.0776	0.0751	0.0718	0.0678	0.0624	0.0798	0.0776	0.0751	0.0718	0.0678	0.0624
		0.1495	0.1473	0.1460	0.1439	0.1428	0.1413	0.1393	0.1473	0.1460	0.1439	0.1428	0.1413	0.1393
		0	0	0	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0	0	0	0

Table D5: P_i: L2A2 grenade ($P_{occurrence}$ = 1)

P_i / 1 for No. 36 Mills Grenade														
Incapacitation criterion	**Matrix name**	**Armour level**												
		U	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Serious	pis36	0.5181	0.4344	0.3336	0.2258	0.1584	0.1389	0.1380	0.4344	0.3336	0.2258	0.1584	0.1389	0.1380
		0.6279	0.6055	0.5213	0.4340	0.3661	0.3555	0.3545	0.6055	0.5213	0.4340	0.3661	0.3555	0.3545
		0.5290	0.5158	0.5045	0.4909	0.4826	0.4786	0.4775	0.5158	0.5045	0.4909	0.4826	0.4786	0.4775
		0.5826	0.5581	0.5423	0.5225	0.5084	0.5026	0.5025	0.5581	0.5423	0.5225	0.5084	0.5026	0.5025
		0.9263	0.9158	0.9040	0.8828	0.8686	0.8600	0.8559	0.9158	0.9040	0.8828	0.8686	0.8600	0.8559
Lethal	pil36	0.1896	0.1369	0.1051	0.0691	0.0484	0.0415	0.0414	0.1369	0.1051	0.0691	0.0484	0.0415	0.0414
		0.0700	0.0564	0.0489	0.0403	0.0346	0.0335	0.0335	0.0564	0.0489	0.0403	0.0346	0.0335	0.0335
		0.0929	0.0891	0.0876	0.0860	0.0849	0.0843	0.0841	0.0891	0.0876	0.0860	0.0849	0.0843	0.0841
		0	0	0	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0	0	0	0

Table D6: P_i: No.36 Mills grenade ($P_{occurrence}$ = 1)

D.5 GENERATION OF ARMOUR COMBINATIONS (MATLAB® M-FILE)

```
%---------------------------------------------------------------
%Written by C Couldrick, Cranfield University.
%Filename is transform.m .
%Generates all the different possible armour combinations from
%the CASPER output, which is transformed in Microsoft Excel.

%Selects the desired input matrix corresponding to a given threat
%(L2A2 grenade, No. 36 Mills Grenade or a 50-50 probability of
%either) and a given incapacitation criterion (serious or lethal).
q=pill2;

%There are 13 armour levels with the minimum being for the
%unarmoured man (except for his impenetrable head protection).
n=13;
s=0;
unarm=1-(1-q(1,1))*(1-q(2,1))*(1-q(3,1))*(1-q(4,1))*(1-q(5,1));

%Points are generated for every combination of leg, arm, pelvis,
%abdomen and thorax armour. Each one consists of a value for the
%Pi, UF, total weight and total cost.
for le=1:n,
      for ar=1:n,
            for pe=1:n,
                  for ab=1:n,
                        for th=1:n,
                              s=s+1;
                              out1(1,s)=1-(1-q(1,th))*(1-q(2,ab))
                                  *(1-q(3,pe))*(1-q(4,ar))*(1-q(5,le));
                              out1(2,s)=unarm-out1(1,s);
                              out1(3,s)=weight(1,th)+weight(2,ab)
                                +weight(3,pe)+weight(4,ar)+weight(5,le);
                              out1(4,s)=cost(1,th)+cost(2,ab)
                                     +cost(3,pe)+cost(4,ar)+cost(5,le);
                        end
                  end
            end
      end
end
clear q n s unarm le ar pe ab th;

%'out1' is used in optimise.m .
%---------------------------------------------------------------
```

D.6 OPTIMISATION (MATLAB® M-FILE)

```
%-----------------------------------------------------------------
%Written by C Couldrick, Cranfield University.
%Filename is optimise.m .
%Generates a protection optimisation envelope for the 'out1' matrix
%from transform.m .

%NB This program carries out 137,858,120,556 checks.
%To break this down into more manageable chunks for parallel
%processing, limit the range of variable i to portions of the range
%1 to 371,293 then combine the results for all the portions.

q=flipud(rot90(out1));
s=1;

%Starts at the origin.
out2(1,1)=q(1,1);
out2(1,2)=0;
out2(1,3)=0;
out2(1,4)=0;

%Selects each point in turn and checks it against all other points.
%If it provides greater or equal protection (UF value) for a lesser
%or equal total weight and/or total cost, then the point is retained.
for i=1:371293,
      n=0;
      for j=1:371293,
            if q(i,3)>=q(j,3)
                  if q(i,4)>=q(j,4)
                        if q(i,1:2)==q(j,1:2)
                        else
                           n=max(n,q(j,2));
                        end
                  end
            end
      end
      if q(i,2)>n
            s=s+1;
            out2(s,1)=q(i,1);
            out2(s,2)=q(i,2);
            out2(s,3)=q(i,3);
            out2(s,4)=q(i,4);
      end
end
clear q s i n j;

%Plots the optimum armour solutions as points.
%Axes are total weight (x), total cost (y) and UF (z).
plot3(out2(:,3),out2(:,4),out2(:,2),'k.');

%'out2' is used in zoom.m .
%-----------------------------------------------------------------
```

D.7 CONSTRAINED OPTIMISATION (MATLAB® M-FILE)

```
%----------------------------------------------------------------
%Written by C Couldrick, Cranfield University.
%Filename is zoom.m .
%Constrains the protection optimisation envelope for
%2 x weight + cost = constant, C.

%Uses the 'out2' from optimise.m .
q=out2;
for i=1:max(size(q)),
      a(i,1)=q(i,2);
      a(i,2)=q(i,3);
      a(i,3)=q(i,4);
      a(i,4)=2*a(i,2)+a(i,3);
end
a=sortrows(a,4);

%Starts at the origin.
out3(1,1)=a(1,1);
out3(1,2)=a(1,2);
out3(1,3)=a(1,3);
out3(1,4)=a(1,4);
s=1;

%Selects each point in turn and checks it against all other points.
%If it provides greater or equal protection (UF value) for a lesser
%or equal value of C, then the point is retained.
      if a(j,1)>out3(s,1)
            s=s+1;
            out3(s,1)=a(j,1);
            out3(s,2)=a(j,2);
            out3(s,3)=a(j,3);
            out3(s,4)=a(j,4);
      end
end
clear q i a j s;

%Plots the optimum armour solutions as points.
%Axes are C (x) and UF (y).
plot(out3(:,4),out3(:,1),'k.');
%----------------------------------------------------------------
```

D.8 POINT TRACE (MATLAB® M-FILE)

```
%----------------------------------------------------------------
%Written by C Couldrick, Cranfield University.
%Filename is trace.m .
%Traces a point to a position in the matrix 'out1' that comes from
%transfrom.m .

%x = weight coordinate
%y = cost coordinate
%z = UF coordinate

%The point is checked against those in the matrix within a tolerance
%of plus or minus 0.00005. Row 4 of the output ('out4') is the
%position in the matrix, which is used to identify the correct
%combination of armour.
s=0;
for i=1:371293,
      if q(2,i) > z-0.00005
            if q(2,i) < z+0.00005
                  if q(3,i) > x-0.00005
                        if q(3,i) < x+0.00005
                              if q(4,i) > y-0.00005
                                    if q(4,i) < y+0.00005
                                          s=s+1;
                                          out4(1,s)=q(2,i);
                                          out4(2,s)=q(3,i);
                                          out4(3,s)=q(4,i);
                                          out4(4,s)=i;
                                    end
                              end
                        end
                  end
            end
      end
end
clear q s i z x y;
%----------------------------------------------------------------
```

D.9 GENERATION OF *UF** RANGES (MATLAB® M-FILE)

```
%----------------------------------------------------------------
%Written by C Couldrick, Cranfield University.
%Filename is getuf.m .
%Generates the different minimum and maximum values of UF* from
%the CASPER output, which is transformed in Microsoft Excel.

%Selects the desired input matrix corresponding to a given threat
%(L2A2 grenade, No. 36 Mills Grenade or a 50-50 probability of
%either) and a given incapacitation criterion (serious or lethal).
q=pill2;

%There are 13 armour levels with the minimum being for the
%unarmoured man (except for his impenetrable head protection).
n=13;
for i=1:n,
      uf_max(1,i)=(q(1,1)-q(1,i))*(1-q(2,n))*(1-q(3,n))*(1-q(4,n))
                                                      *(1-q(5,n));
      uf_max(2,i)=(q(2,1)-q(2,i))*(1-q(1,n))*(1-q(3,n))*(1-q(4,n))
                                                      *(1-q(5,n));
      uf_max(3,i)=(q(3,1)-q(3,i))*(1-q(2,n))*(1-q(1,n))*(1-q(4,n))
                                                      *(1-q(5,n));
      uf_max(4,i)=(q(4,1)-q(4,i))*(1-q(2,n))*(1-q(3,n))*(1-q(1,n))
                                                      *(1-q(5,n));
      uf_max(5,i)=(q(5,1)-q(5,i))*(1-q(2,n))*(1-q(3,n))*(1-q(4,n))
                                                      *(1-q(1,n));
      uf_min(1,i)=(q(1,1)-q(1,i))*(1-q(2,1))*(1-q(3,1))*(1-q(4,1))
                                                      *(1-q(5,1));
      uf_min(2,i)=(q(2,1)-q(2,i))*(1-q(1,1))*(1-q(3,1))*(1-q(4,1))
                                                      *(1-q(5,1));
      uf_min(3,i)=(q(3,1)-q(3,i))*(1-q(2,1))*(1-q(1,1))*(1-q(4,1))
                                                      *(1-q(5,1));
      uf_min(4,i)=(q(4,1)-q(4,i))*(1-q(2,1))*(1-q(3,1))*(1-q(1,1))
                                                      *(1-q(5,1));
      uf_min(5,i)=(q(5,1)-q(5,i))*(1-q(2,1))*(1-q(3,1))*(1-q(4,1))
                                                      *(1-q(1,1));
      for j=1:5,
            out_uf(j,i)=(uf_max(j,i)+uf_min(j,i))/2;
            out_uf((j+5),i)=(uf_max(j,i)-uf_min(j,i))/2;
      end
end
clear q n i uf_max uf_min;

%'out_uf' is used in grafuf.m .
%----------------------------------------------------------------
```

D.10 GRAPHICAL OUTPUT OF *UF** RANGES (MATLAB® M-FILE)

```
%----------------------------------------------------------------
%Written by C Couldrick, Cranfield University.
%Filename is getuf.m .
%Generates a bar chart of the minimum UF* values superimposed on
%the maximum UF* values.

colormap gray;
bar(out_uf(1:5,2:7)+out_uf(6:10,2:7));
legend;
hold on;
bar(out_uf(1:5,2:7)-out_uf(6:10,2:7));
hold off;

%Further, manual colour manipulation is required to distinguish
%between the two data sets.
%----------------------------------------------------------------
```

D.11 CONFERENCE PAPER

Personal Armour Systems Symposium (PASS2002), The Hague, Netherlands. 18-22 Nov 2002.

OPTIMISATION OF PERSONAL ARMOUR FOR PROTECTION

CA Couldrick, PL Gotts and Dr MJ Iremonger

Abstract

This paper uses a systems approach to develop a theory of personal armour optimisation to apply to any scenario regardless of the injury mechanism. It is important for military personal armour, which can always be overmatched. Moreover, it is argued that police body armour is a simplified case in the same design system.

The concept of usefulness factor[1] (*UF*) and protection optimisation envelope are developed for materials selection. A theoretical military scenario is chosen in order to demonstrate the two concepts. Eleven theoretical armours are derived from a single initial material. A casualty reduction analysis model (CASPER[2]) is then used to simulate the scenario with each armour. This provides a basis for discussing the advantages and disadvantages of both the *UF* and protection optimisation envelope for material selection. Additionally, it is demonstrated how CASPER can be developed to provide weight and cost – as well as protection – estimates for an armour.

It is found that *UF** – the reduction in the probability of incapacitation due to wearing a given section of armour – can be used for qualitative material selection. This is most useful for the lethal incapacitation criterion. Alternatively, a protection optimisation envelope can be used for quantitative material selection. This is computationally expensive but becomes more useful as quantitative ergonomic and financial models are developed.

Introduction

The role of the armour designer is to afford the best possible protection to the wearer. This is achieved by removing them from danger or increasing the protection level of the armour. The danger is reduced first e.g. by staying out of the direct line-of-fire. However, if a person must still work in a dangerous scenario then armour can be worn to reduce the chance of injury or death. The aim of this paper is to develop theory and tools to select optimum combinations of materials that provide the best possible protection.

The concept of 'best possible protection' is based on four assumptions. Firstly, any potential armour material has negative attributes such as a high price or areal density. This means that it is not possible simply to continue adding armour: no garment can provide absolute protection from all threats so there must be trade-offs to optimise.

Secondly, the wearer does not care what part of their body is injured, only that they are incapacitated to a greater or lesser degree. It does not matter whether a person is killed due to a head or chest injury: they are still dead. Nevertheless, the probability of incapacitation (*Pi*) depends on factors such as threat position, wearer posture and vulnerability. This means that different protection levels may be required for different body regions. Therefore, protection must be optimised across the whole body.

Thirdly, multiple threats and injury mechanisms may occur in the same body region. For example, a variety of fragment sizes and a blast wave may interact with the wearer's torso. The armour designer must balance protection based on the relative likelihood of each threat type. Hence, it is necessary to select 'optimum combinations of materials' within – as well as between – body regions.

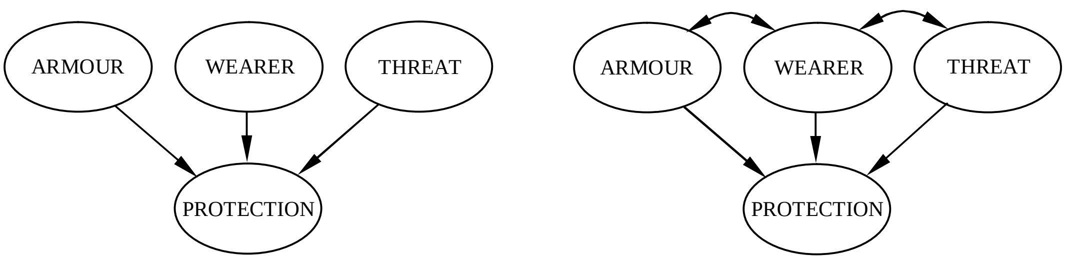
Fourthly, protection is time dependent because armour can be donned or doffed and shields can be picked up or put down. It may be preferable to wear a lightweight garment constantly rather than a heavier but more threat-resistant armour intermittently or vice versa. Therefore, the designer should optimise protection for the duration of a task or mission.

These assumptions are the foundations of protection optimisation for personal armour. They can be summarised as choosing the right armour for the right area of the body at the right time, subject to ergonomic and financial constraints. A systems approach to making this design decision is developed in the following section.

Theory

Systems Thinking

Systems thinking is not new. Plato[3] used it in the Western world around 400BC in an attempt to improve society. Sun Tzu[4] used it to win wars in the East at about the same time. Basically, a system is more than the sum of its constituent parts due to the interactions between them. An illustration of a simple personal armour system is given in Figure 1b. It shows that *Pi* is defined not only by the threat-resistance of the armour, but also by the increase in threat due to e.g. a degradation in ergonomic performance.



Figures 1a and b: Non-systems and Simple Systems Representations of Personal Armour

The Personal Armour Design System

A system needs definition (a boundary, components, inputs, outputs and interactions) and central objectives against which to make improvements. The boundary for personal armour design includes the components of armour, available materials, wearer, task, threat and environment. A graphical representation of the personal armour system is given in Figure 2.

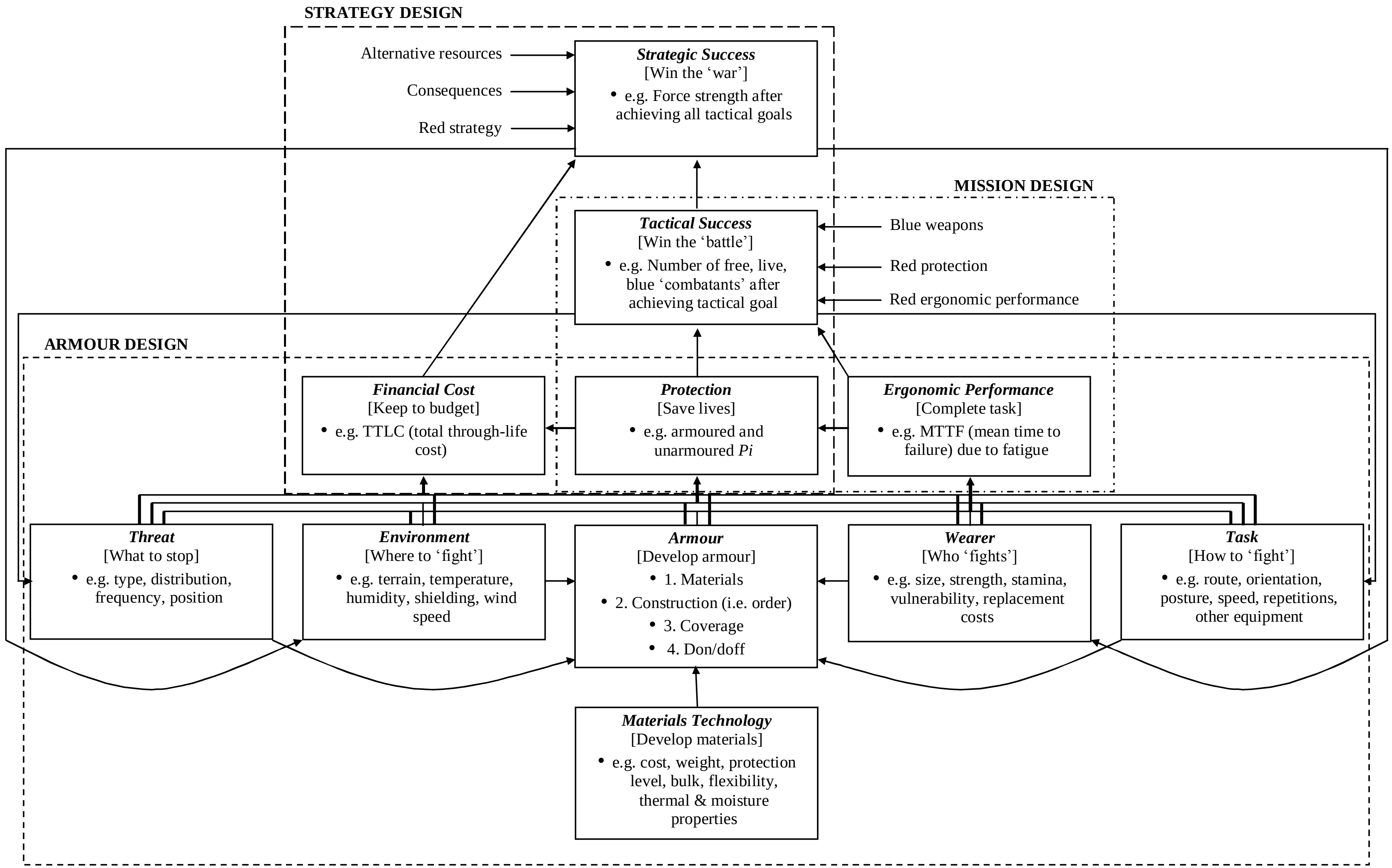


Figure 2: A Representation of the Personal Armour System

The decision of what to include within the system boundary affects the output. For example, the operational commander would want to include the 'stopping power' of allied weapons and the actions of the enemy. Ashby[5] uses this systems level in a computational combat simulation named Janus[6] to assess the success of an offensive infantry mission to capture an enemy position. However, it is proposed that this is the level above personal armour design. The armour designer is not required to estimate whether a particular mission will be successful. He or she *is* obliged to provide the commander with sufficient information to make that decision. In return the commander must inform the designer of any changes to the threat or task as a result of wearing armour. Hence, there are three outputs from the personal armour design system that are central objectives. These are protection, ergonomic performance and financial cost. Protection is defined as a reduction in the probability of wearer injury. Ergonomic performance is a reduction in the ability of the person to complete the task e.g. because of fatigue or over-heating. These enable the operational commander to select tactics. Financial cost is the additional output that enables the strategist to choose between alternative technologies such as tanks or air-strikes.

Using this view of the system, the role of the personal armour designer is as follows. (1) Capture information about the threat, environment, wearer, task and available materials. (2) Select the optimum combinations of armour materials, coverage and wear time. (3) Provide clear information to the operational analyst about the range of protection-ergonomic performance-financial cost combinations that are possible. (4) Capture any changes in threat, environment, wearer and task due to wearing armour. (5) Iterate this design process until an acceptable garment is produced or shown to be impossible.

This paper concentrates on the primary objective of personal armour design – protection. Therefore, the protection subsystem is developed in detail in the next subsection, while only the most basic ergonomic and financial constraints of weight and material cost are used in the computational simulation.

Protection Subsystem

Military armour such as fragmentation vests, countermine suits and Explosive Ordnance Disposal (EOD) suits can always be overmatched. They are designed to offer a degree of – rather than absolute – protection from threats that include grenades, mines and shells. These may produce a variety of fragments and blast waves that cannot be stopped using current materials without imposing unacceptable ergonomic and financial burdens. Thus, casualty reduction analysis is used to estimate the probability of incapacitation (*Pi*) of the wearer when faced with a given scenario. The reduction in *Pi* due to wearing armour is *the* measure of protection and is described[1] as the usefulness factor (*UF*).

It is proposed that *UF* is estimated in five stages that are henceforward named *occurrence*, *incidence*, *resistance*, *incapacitation* and *protection* (see Figure 3). 'Occurrence' defines the likelihood of each particular event (threat type, range, orientation, etc.) existing at a given time. It is a product of the threat and task, such as the density of and route through a minefield.

'Incidence' describes the likelihood of particular threat characteristics striking a person. It depends on the threat distribution relative to them. Initially, this is defined by the dispersal of e.g. fragments or blast waves in an unrestricted environment as found from arena trials or free-field blast wave propagation theory. Modifications then occur due to interactions with the environment such as the effects of shielding, air drag and surface reflections. If an armour is hit, its ability to stop the threat must be evaluated.

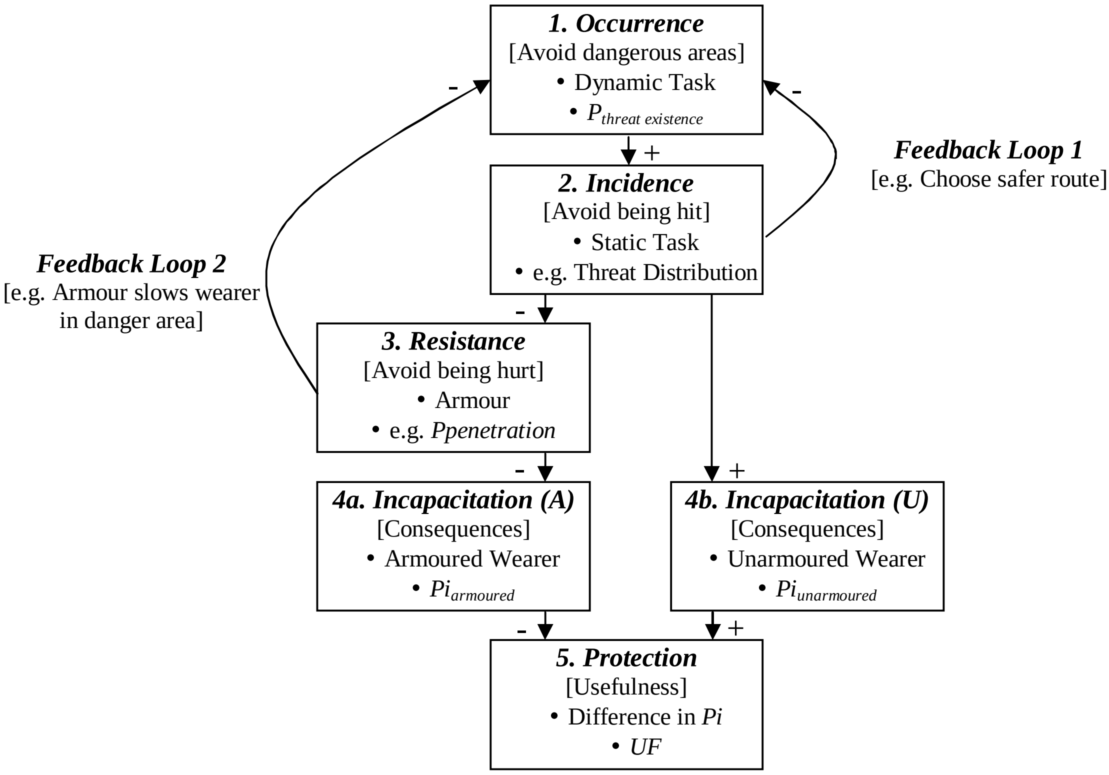


Figure 3: Five-stage Estimation of Protection

'Resistance' defines the residual properties at the back face of the garment. The choice of which attributes to use depends on the type of threat. For example, a description of the penetration of fragments should include their masses, residual velocities and probabilities of defeating the armour (see Kneubuehl[7] and Tobin[8]). This allows the designer to link the models of armour resistance and incapacitation.

Pi is calculated from a model of wearer 'incapacitation' due to the threat behind the garment, such as Kokinakis-Sperrazza[9] for fragments and Bowen et al[10] for blast. Incapacitation models such as these may be derived from a variety of sources including accident reports, biomechanical simulations and cadaver or animal experiments. A great deal of subjective interpretation by medical experts is often required to assess the results. Nevertheless, it is important that all the stages link together regardless of whether they are modelled or measured from experiments. It is then possible to estimate *Pi* for each threat and area of the body, regardless of the injury mechanism, subject to a common incapacitation criterion such as death. However, the assumptions in the Introduction imply that it does not matter how or where a person is killed: they are still dead. Binomial combination is used to obtain *Pi* for the whole body from the separate threats to individual body regions as demonstrated below.

$$(1 - Pi_{total}) = (1 - Pi_{fragment,head}).(1 - Pi_{blast,torso})\ldots \tag{1}$$

Moreover, it does not matter when an incapacitation occurs. It should be noted that, since the task is dynamic, *Pi* is a function of time. If the wearer is assumed to doff their armour at the end of task, when *Pi(t)* is approximately 0, then the following equation is used.

$$Pi\left(0 < t < T\right) = \frac{\int_0^T Pi\left(t\right).dt}{T} \tag{2}$$

$Pi(0<t<T)$ = probability of incapacitation occurring during task
$Pi(t)$ = probability of incapacitation occurring at time t
T = task duration

Finally, 'protection' is estimated with the usefulness factor (*UF*) as derived by Couldrick and Gotts[1]. This is the reduction in *Pi* due to wearing armour as shown below. It is the benefit of protection that is traded off against ergonomic and financial penalties.

$$UF = Pi_{unprotected} - Pi_{armour} \tag{3}$$

A casualty reduction analysis computer program named CASPER[2] estimates *Pi* with and without ballistic armour, for a static event with a probability of occurrence of 1 (i.e. stages two to four). If a sequence of simulations – each with an associated probability of occurrence – are combined then a dynamic task can be represented. This program is used later in this paper to demonstrate the ideas set out here. It is used for military personal armour design and could be used for police ballistic vests.

Police – in contrast with military – personal armour is designed to stop a threat absolutely for a limited area of the body as outlined in the various test standards. Protection is restricted to the regions most likely to be hit by a threat that can cause serious injury, i.e. excluding the arms and legs. This is a reasonable assumption if the threat is targeted such as a knife or bullet, or if any injury to the arms or legs is deemed acceptable. In these cases a set of threats is assumed absolutely to occur and be distributed so that the armour is hit with specific properties. This means that stages one and two of the calculation of *Pi* are ignored. Moreover, the choice of bullets or knives is such that they can be stopped 'absolutely.' For example, a ballistic vest is designed to stop all of the specified bullets, whilst making blunt trauma unlikely. Alternatively, stab resistant armour is accepted only if the penetration of specified knife threats is limited to a distance that is deemed unlikely to cause serious injury. This means that an incapacitation model in stage four is redundant. These assumptions simplify the design down to a single go-no go decision: Does the garment stop the specified threat? Hence, current police body armour is a simplified case of the same design system as military personal armour.

If the simplifying assumptions behind police armour change then there will be a direct need to use the five stage model. For example, if a proportion of bullets used against the police were armour-piercing would ballistic vests still be useful? There is also another, indirect reason for all armour designers to consider the implications of a systems view of the five stage model: There are two feedback loops that affect the person's chances of being incapacitated.

The first feedback loop is negative and shows that it is possible to make tasks safer by choosing paths that offer the lowest likelihood of being hit. This point has been demonstrated by Couldrick and Gotts[1] for an EOD operator approaching unexploded munitions. If the orientation of the device is known, it is possible to minimise *Pi* for the unarmoured person. This is equivalent to minimising the probability of being hit by anything likely to be injurious.

The second feedback loop is also negative and highlights the threat increase (occurrence) as a result of wearing armour. For example, Ashby[5] demonstrates that infantry soldiers wearing heavy, more threat-resistant armour can be more likely to die than those wearing lighter, less threat-resistant garments. This is due to slow-moving infantrymen being exposed in a danger zone for longer than faster ones. The implications of the two feedback loops in optimising personal armour for protection are demonstrated in the following subsection.

An Example of Feedback in the Protection Subsystem

The two feedback loops in the protection subsystem can affect the usefulness of armour. This phenomenon is demonstrated using the trends from the following theoretical military scenario.

1. An EOD operator is assumed to inspect a fictional, cylindrical fragmentation device. The threat has a vertical axis of symmetry and is the same height as the person. Hence, it is reasonable to approximate *Pi|occurrence(x)* as inversely proportional to the horizontal range (*x*). Air drag is neglected.
2. The threat is set to operate on a random timer. Therefore, the probability that the device detonates is constant throughout the task. The probability of this happening (*Poccurrence(t)*) is 0.5.
3. The task is to approach to within 1m of the device from outside its lethal range (*R*); inspect it for 10 seconds; withdraw to safety. The unarmoured operator moves at $2ms^{-1}$. The lethal range is defined as *x* when *Pi(x)* = 0.01 for the unarmoured, standing person.
4. The wearer can make the task safer by adopting a crouching posture. This has the effect of reducing his or her exposed surface area by 15%. Therefore, *Pi|occurrence(x)* for a crouched person is approximated as 15% less than for an exposed one.
5. The effects of armour are assumed to be twofold. Firstly, enough fragments are stopped or slowed to reduce *Pi|occurrence(x)* by 20%. Secondly, the ergonomic penalty is that the armoured operator moves at $1.5ms^{-1}$.

This scenario is illustrated in the following graphs. Figure 4 shows *Pi|occurrence(x),* which is the probability of incapacitation given that the device detonates while the operator is at *x*. The four alternatives reflect the possible combinations of reducing incidence (adopting a safer posture) or increasing resistance (wearing armour). *R* is found to be 50m by combining *Pi|occurrence(x)* and *Poccurrence(t)*.

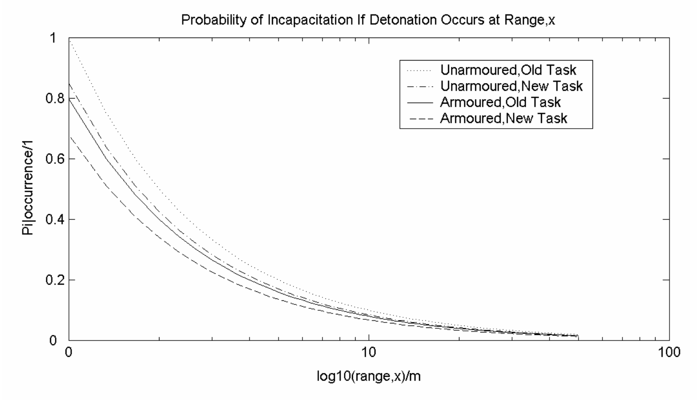


Figure 4: *Pi|occurrence(x)* for a Theoretical EOD Inspection

Once *R* and the operator's speed (*x'(t)*) are known the task (*x(t)*) is defined, as shown in Figure 5. This demonstrates that an armoured person spends longer in a danger zone than an unarmoured one. Although both people finish the task at the same range, their end time (*T*) is 75.33 or 59s respectively.

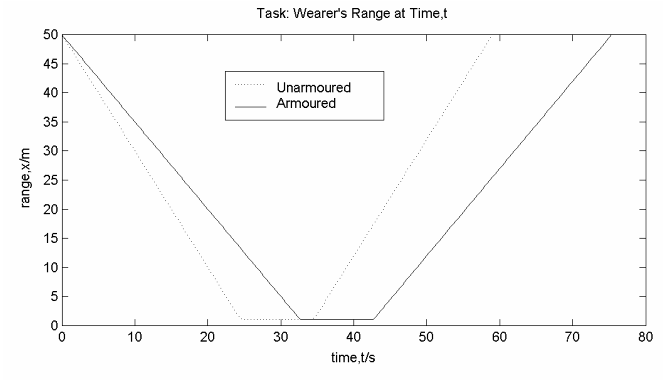


Figure 5: Task *x(t)* for a Theoretical EOD Inspection

Pi|occurrence(x), x(t) and *Poccurrence(t)* are combined to give *Pi(t)*. This is illustrated in Figure 6. *Pi* for the entire duration of the task is then derived using Equation 4.

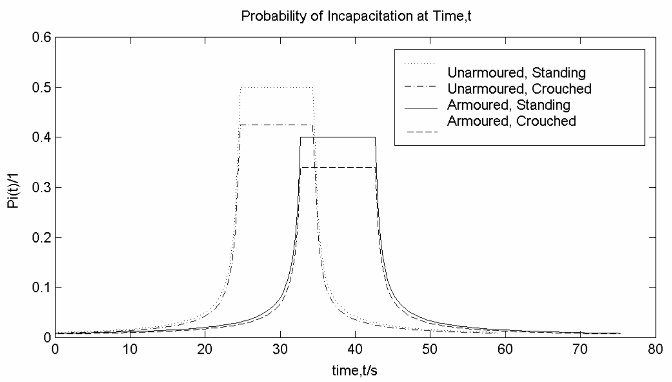


Figure 6 *Pi(t)* for a Theoretical EOD Inspection

The computed values of *Pi* for the four alternatives are given in Table 1. These provide four different measures of *UF*. The first value (*i*) is obtained if the task remains unchanged. It ignores the benefit that can be achieved by making the task safer. Hence, this measure is an overestimate of the true usefulness of armour. It should be discarded. Likewise, value *ii* is an overestimate because it includes the advantage of altering the operator's posture. It should be rejected too. Value *iii* is an underestimate because it reflects the wearer choosing to make their task more hazardous than necessary. It should also be discarded. The final value (*iv*) is the true usefulness of armour. Therefore the definition of <u>*UF* is refined as: the reduction in *Pi* after any reasonable reduction in incidence, due to wearing armour</u>.

Number	Unarmoured		Armoured		UF
	Task	$Pi_{unarmoured}$	Task	$Pi_{armoured}$	
i.	Standing	0.118	Standing	0.081	0.037
ii.	Standing	0.118	Crouched	0.069	0.049
iii.	Crouched	0.100	Standing	0.081	0.019
iv.	Crouched	0.100	Crouched	0.069	0.031

Table 1: Alternative Measures of Protection for a Theoretical EOD Inspection

This example demonstrates the importance of a systems approach to personal armour design. If either feedback loop is ignored then the estimated usefulness of – and therefore the estimated number of lives saved by – armour is wrong. Therefore, the armour designer must not only provide the operational analyst with a 'best estimate' of protection but also iterate the design process to improve the estimate. Two methods of optimising and presenting the protection offered by possible designs are developed in the following subsections.

*Optimisation of the Protection Subsystem 1: UF**

The first method of optimising personal for protection is to use *UF**. This is henceforward defined as the reduction in the *Pi* due to wearing a given section of armour. It is the usefulness of each piece of the garment, as given in Equation 4.

$$UF^* = Pi_{without\ armour\ section} - Pi_{with\ armour\ section} \qquad (4)$$

If the designer is able to distinguish between the sections of armour that offer the greatest protection, he or she can build an optimum whole body solution. However, it does not matter when, where or how a person is incapacitated. If a person is guaranteed to die from a head wound, blast injury or when the garment is doffed, no amount of fragmentation protection over the chest is useful. Conversely, if the rest of the body is always protected absolutely, against all threats then the wearer's life depends solely on that single piece of armour. Hence, *UF** varies according to the protection afforded by the rest of the garment. The minimum occurs when the wearer is unarmoured except for the section under consideration. The maximum is the result of wearing the best possible protection except for the section under consideration. If the difference between the minimum and maximum is relatively small compared with the average value, then *UF** can be used to identify the armour sections that offer the most protection.

Optimisation of the Protection Subsystem 2: Protection Optimisation Envelope

The second method of optimising personal armour is to use the concept of a *protection optimisation envelope*. This is the boundary that defines the maximum possible *UF* for a given combination of ergonomic and financial constraints. It shows the best armour solutions that are available. The method of producing and using a protection optimisation envelope are described below.

Each armour design and pattern of usage (when to don and doff parts of the garment) has an associated level of protection, ergonomic penalty and financial cost. These form a cloud of possible solutions as shown in Figure 7. This diagram is presented in three dimensions but could be extended to include – although not graphically represent – any number of constraints such as total weight, rate of heat storage, time to wearer fatigue, etc. The main point to note is that not all solutions are sensible.

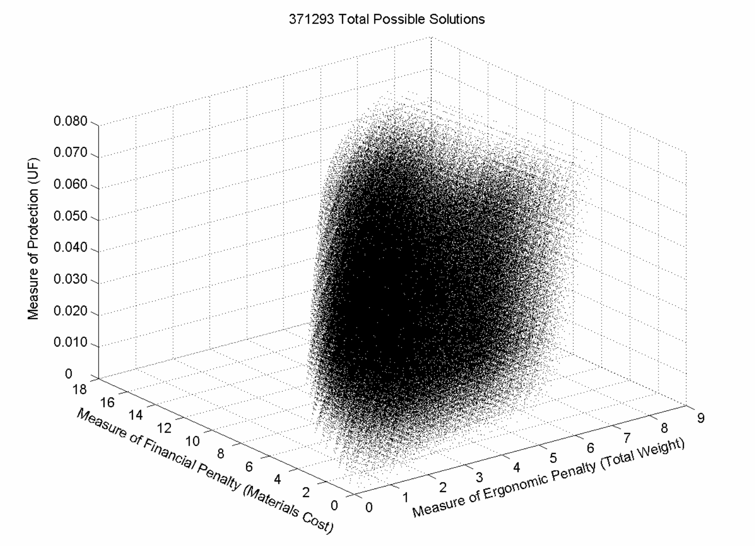


Figure 7: Total Possible Armour Solutions form a Cloud

Figure 7 presents 371293 armour options that are generated later in this paper. However, only some of them are shrewd choices. The next step is to filter out the unwanted ones. This is achieved by comparing each point to the others. If an armour option represents the maximum *UF* at or under its ergonomic and financial constraints (shown here as total material cost and total weight) then it is retained; otherwise it is rejected. In this case, 1448 solutions that give the 'best possible protection' are found. This method of optimisation is reasonable for the armour designer to apply in isolation because there is no bias of the constraints. The result is an *optimisation envelope*.

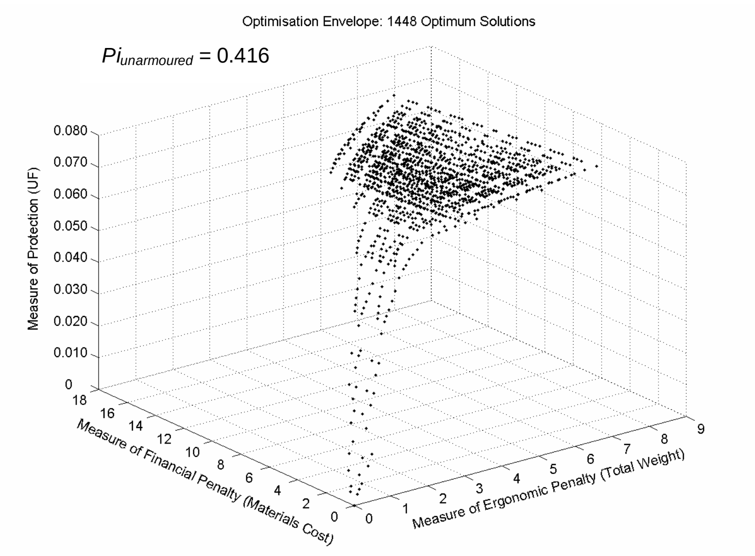


Figure 8: Protection Optimisation Envelope

All points in Figure 8 hold all the information necessary to trace the solution back to the original design (material, coverage, etc.). The envelope can be studied visually to identify ergonomic and financial combinations that are not possible using the available materials. If necessary, the value of $Pi_{unarmoured}$ can be used with *UF* to identify the resultant probability of incapacitation. Most importantly, it draws attention to the regions of greatest increase in protection for the least constraint penalties. This is now a tool that armour designers and other interested parties can use to visualise and discuss personal armour solutions.

An optimisation envelope is the set of best possible, unbiased solutions. If conditions are applied by the wearer, purchaser or operations analyst then a smaller set can be obtained. For example, if weight is twice as important as cost then the best option can be found on each plane corresponding to cost + 2 × weight = constant. This type of condition must not come from the designer because it biases the constraints.

In Figure 9, the optimum armours are found for the stated condition. Any increase of the constant must be associated with an increase of *UF*. In this case, the 371293 possible solutions are reduced to 21 different options. Each point is an optimum: the 'best possible protection' for the stated conditions. Each one can be traced back to the original design (material, coverage, etc.). For example, three interesting solutions are highlighted in Figure 9. The user, purchaser or operations analyst is able to use the measures of protection, ergonomic performance and financial cost to estimate the contribution of armour to tactical success.

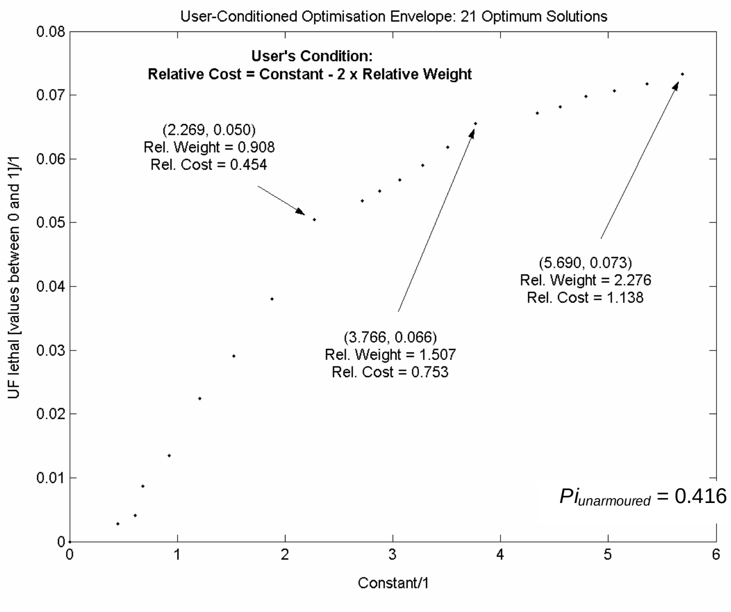


Figure 9: Constrained Optimisation Envelope

A theoretical military scenario is presented in the next section that is used to demonstrate the two methods of optimising personal armour for protection.

Method

Scenarios

The scenarios are that of a standard NATO crouched man[11] as given in CASPER[12]. His environment is the floor plane he is standing on, which offers no shielding. There is a single, stationary grenade (either a No. 36 Mills, an L2A2 or a 0.5 probability of each) placed on the floor at a horizontal range of 2m, which will detonate. It has an equal probability of detonating at any given angle around the man. The grenade's axis is normal to the floor plane with the fuse at the top (illustrated in Figure 10). Although a grenade is unlikely to adopt this orientation in real life, due to its centre of gravity, the calculations are simpler since fragments are distributed axisymmetrically. The man's task is to remain stationary with respect to the grenade. This means that there is no modification of any of the three sets of *Poccurrence*, so the analysis only needs one iteration.

The man's armour is an impenetrable helmet plus visor and a penetrable body suit that does not include the hands or feet. The use of impenetrable head protection simplifies the example by removing the need to consider helmet and visor materials. In a realistic situation the designer cannot ignore this since, if a person is certain to die by a head injury, no armour is useful. The body protection covers five different regions as defined in the *lethal* and *serious* (requiring hospitalisation) summarised Kokinakis-Sperrazza incapacitation criteria proposed by Waldon et al[13]: the torso, abdomen, pelvis, arms, legs. Hence, there are six scenarios with two incapacitation criteria and three sets of *Poccurrence*. Overall, the scenarios are simplistic but they enable demonstration of *UF** and the protection optimisation envelope.

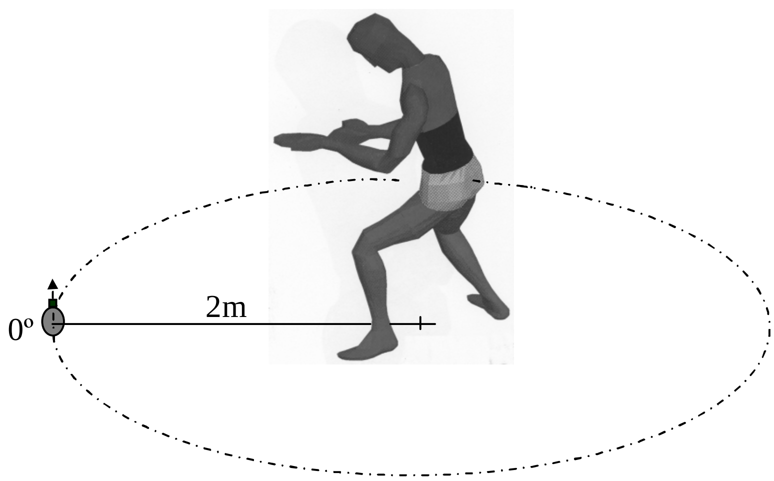


Figure 10: An Unarmoured, Crouched Person 2m from a Vertical Grenade

Armour Options

Six different protection levels are considered for two different materials (*a* or *b*). This gives a choice of twelve different armours plus the option of remaining unarmoured. Any of these can be used on the thorax, abdomen, pelvis, arms and legs. This gives a total of 371,293 (i.e. 13^5) possible armour options.

The initial protection level is based on a real, layered, soft, ballistic armour that is already modelled in CASPER. It has specified strike velocity versus residual velocity (V_s-V_r) profiles for four different fragment masses. These are extrapolated to give the characteristics of five theoretical protection levels. Briefly, the V_s-V_r profile identifies a limit velocity (V_L) above which the projectile has a residual velocity based on Newtonian conservation of energy. This is represented as:

$$V_r = 0 : V_s < V_L \tag{5a}$$
$$V_r^2 = V_s^2 - V_L^2 : V_s > V_L \tag{5b}$$

If the limit velocity for each projectile is increased then it is possible to define the *Vs-Vr* profiles for the new materials. In real life this may not be wholly true (e.g. if the projectile deforms) but it is a reasonable assumption for the creation of theoretical demonstrative armours. This information is saved for each armour in materials file format that is used by CASPER.

The theoretical armours are also given areal density (ρ_A) and cost per unit area ($\$_A$) properties relative to those of the initial material. Tobin[14] found that, for a given fragment and fibre-reinforced plastic armour, $V_{50} \propto \sqrt{(\rho_A)}$, where V_{50} is the statistical mid-point of estimates of a V_L. Hence, despite the differences between fibre-reinforced plastic and soft, layered ballistic armours it is reasonable to assign relative areal densities to the theoretical armours using the following equation for each material (*a* or *b*).

$$\rho_A \propto V_L^2 : \text{material } a \text{ or } b \tag{6}$$

It is reasonable to assume that the purchase cost per unit area of a material is relative to its areal density. Thus, the relative costs per unit area of the theoretical armours are given from the following equation for each material (*a* or *b*).

$$\$_A \propto \rho_A : \text{material } a \text{ or } b \tag{7}$$

In order to complete definition of the theoretical armours relative to the initial one, it is necessary to specify the cost per unit area and areal density of material *b* relative to material *a* for a given protection level. If material *b* is defined as being 90% of the weight but four times as expensive as material *a* to achieve the same protection, the following table of relative material properties can be drawn.

Code	**U**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Material	–	a	a	a	a	a	a	b	b	b	b	b	b
V_L	0	1	1.2	1.4	1.6	1.8	2	1	1.2	1.4	1.6	1.8	2
ρ_A	0	1	1.4	2.0	2.6	3.2	4	0.9	1.3	1.8	2.3	2.9	3.6
$\$_A$	0	1	1.4	2.0	2.6	3.2	4	4	5.8	7.8	10.2	13.0	16

Table 2: Properties of Theoretical Armours Relative to Material *a*

Area of Incapacitation

Geometry data from CASPER is used to define the surface area of the thorax, abdomen, pelvis, arms (excluding hands) and legs (excluding feet). This is used to calculate the total mass and cost of armour required to cover each of the five body regions. The source data is taken from CASPER's representation[12] of the NATO standard 'standing man'[11]. The geometry of the man – rather than the armour – is used because it is divided clearly into Kokinakis-Sperrazza's body regions. A standing – rather than crouched – man is used for two reasons. Firstly, the undeformed surface area of the body is calculated. This is the shape personal armour is designed to fit originally. Secondly, it simplifies the transformation of the CASPER geometry file into a surface area estimate. CASPER represents the human body as divided into triangulated sections or 'boxes'. For the standing man, the planes between sections are normal to CASPER's y- or z-axes. The three-dimensional co-ordinates of each node on the surface of a box are given in a geometry file. This file can be opened in a spreadsheet such as Microsoft Excel 2000 in order to convert the co-ordinate data into a surface area.

Figure 11: CASPER's triangulated representation of the NATO standard standing man

Pythagoras' theorem in three dimensions is used to calculate the side length of each triangle. This is then be used to find the area of each triangle and, hence, the surface area of a section. However, the area of any plane between boxes must be subtracted from the total because this does not correspond to the real human body. Therefore, it is possible to calculate the surface area of each body region as given in Table 3.

Region	**Area/m^2**
Thorax	0.227
Abdomen	0.150
Pelvis	0.192
Arms	0.459
Legs	1.001

Table 3: Surface Area of Body Regions

Simulation and Optimisation

CASPER is a casualty reduction analysis model that simulates the effects of fragmenting munitions on a target. It calculates the position and relative velocities of each fragment from an exploding device. The action of any garment or shielding is included before the effects on the person are determined. *Pi|occurrence* with and without armour is then calculated using the summarised Kokinakis-Sperrazza criteria[13]. A more detailed explanation of the theory behind CASPER is described by Grout[15] or Couldrick and Gotts[1]

CASPER is used to simulate the given scenario with either the L2A2 or No. 36 Mills grenade in a single run. The equal probability of a device detonating at any angle around the man is approximated by averaging *Pi|occurrence* at every 45° increment. A simulation run is required for each armour. There are 2 threats and 12 different armours (excluding the unarmoured option). Therefore, 24 simulations runs are carried out.

The output from each simulation run is a text file that contains the values of *Pi|occurrence* for each incapacitation category, body region and 45° increment. A spreadsheet (Microsoft Excel 2000) is used to collate the files, removed extraneous information and calculate the averages. The resulting output is a table of *Pi|occurrence* values for each threat of incapacitation category, armour (including the unarmoured option) and body region. These are multiplied with *Poccurrence* (0, 0.5 or 1) to obtain a table of *Pi* values for each armour section.

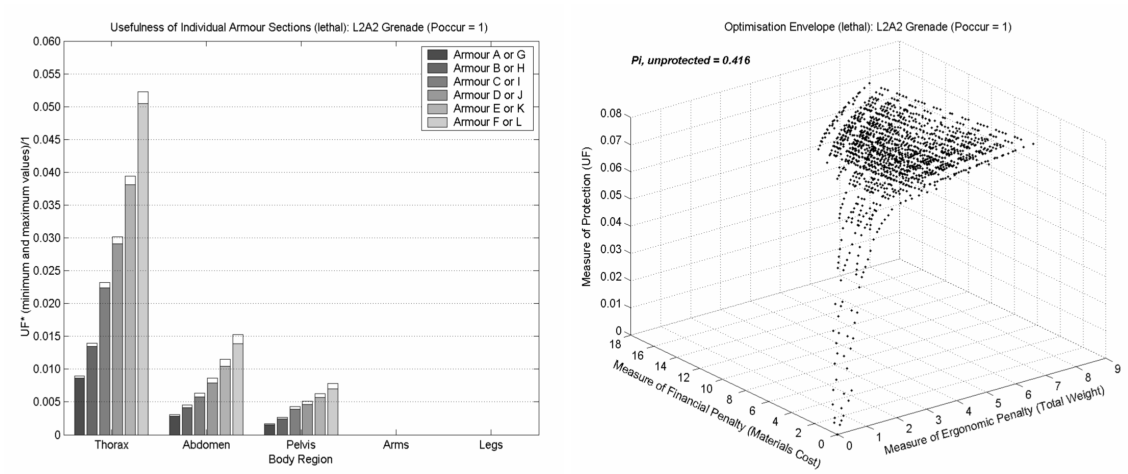
*UF** is relatively simple to calculate in Microsoft Excel using Equation 4 because only two values (the maximum and minimum) are required for each armour section. Thus, only 120 points are needed (12 armours × 5 body regions × 2). This is reduced by half due to the identical protective properties of materials *a* and *b*.

Conversely, the protection optimisation is too large to compute in Excel so Matlab 6.1 is used. *UF*, Total weight and Total materials cost are generated for each of the 371,293 armour solutions. *UF* is calculated using Equations 1 and 3. There is no need to use Equation 2 because *Poccurrence* remains constant with respect to time. Total weight and Total materials cost are found by summing the multiples of Area and ρ_A or $\$_A$ respectively (given in Tables 2 and 3). Afterwards, the optimisation algorithm compares each point against all of the others i.e. 137,858,120,556 checks. Although this is not efficient it is the most accurate method of obtaining a protection optimisation envelope.

Results

Once the CASPER simulation results have been imported into Excel or Matlab, the graphs of *UF** are produced in a matter of minutes. However, generating the optimisation envelope for each scenario takes around 20 computer-days on a current standard PC (e.g. Pentium 4 1GHz). The protection optimisation envelope and a theoretical user-constrained optimisation envelope (for cost + 2×relative weight = constant) are now presented, together with graphs of *UF** for each scenario.

L2A2 Grenade (Poccurrence=1), Lethal



Figures 12a and b: Lethal *UF and Optimisation Envelope for an L2A2 Grenade (*Poccurrence* = 1)**

UF* (Figure 12a) shows clearly that, for the lethal incapacitation criterion, it is most important to protect the thorax. The next most important body region is the abdomen. However, this has to have at least armour levels E or F (or K or L) to offer as much protection as can be obtained on the thorax. The last consideration is to protect the pelvis. Moreover, it would seem that the arms and legs should not be protected at all. This is because the Kokinakis-Sperrazza lethal incapacitation model does not count injuries to the limbs.

The protection optimisation envelope (Figure 12b) demonstrates that there are 1448 optimum armour solutions. However, the final choice depends upon the customer's prioritisation of protection, ergonomic performance and financial cost. There is a sharp rise in protection where the relative weight and cost are less than 3 and 6 respectively. Afterwards, the rise in protection is much shallower. This is due to the best armour solutions being combinations of armour levels on the thorax, abdomen and pelvis. The shallow rise section reflects the addition of leg and arm protection. This is counted in this model because there is a small chance that fragments may penetrate the arms or legs and enter the pelvis or torso, which *UF** does not show.

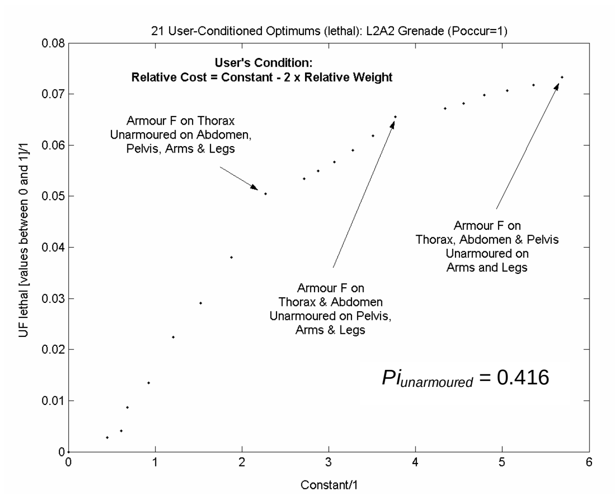


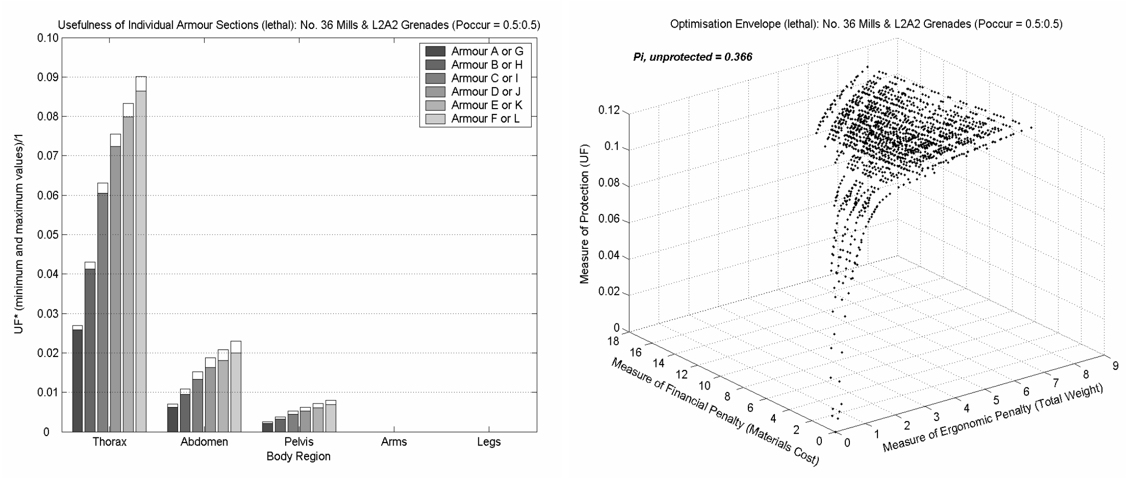
Figure 13: Lethal Constrained Optimisation Envelope for an L2A2 Grenade (*Poccurrence* = 1)

The user-constrained optimisation envelope (Figure 13) highlights 21 solutions for the condition that weight is twice as important as cost. Three interesting points are selected: two where the gradient changes and one at the maximum possible protection. These show that, under this condition, it is a good idea to cover – in priority order – the thorax, abdomen and pelvis with armour F. This fits very well with the knowledge gained using *UF**.

Either optimisation envelope can be used to identify that the maximum protection possible in this scenario is $UF \approx 0.07$. In other words, it is expected that 7 percent of people in this scenario who would otherwise die, can be saved. Whether this is a big enough benefit for the weight and cost penalties if for the user, purchaser, commander or operations analyst to decide.

36 Mills & L2A2 Grenades (Poccurrence=0.5:0.5), Lethal

Figure 14a show that it is even more important to protect the thorax against a 50-50 chance of an L2A2 of No. 36 Mills grenade detonation than for a guaranteed L2A2 explosion. No considered armour on any other area of the body can offer as much protection. Moreover, the values of *UF** indicate that armour can offer more defence against the No. 36 Mills grenade than the L2A2 device. This is unsurprising because the later is more modern and a better weapon than the former.



Figures 14a and b: Lethal *UF and Optimisation Envelope for No. 36 Mills (*Poccurrence* = 0.5) & L2A2 (*Poccurrence* = 0.5) Grenades**

This protection optimisation envelope (Figure 14b) also demonstrates a sharp rise in *UF*, for the same reasons as before. One of the useful features of this type of diagram – especially if viewed from above – is that it is simple to identify combinations of constraints that are not possible. For example, no matter how much money one spends over a relative price of approximately 4, there is no armour that has a relative weight less than about 2.

In Figure 15 the 1507 optimum points are whittled down to 29 user-constrained solutions. The first highlighted point is for armour E on the thorax only. More importantly, it is not armours F or L on the thorax. This level of selection is not possible without using constraints. It is possible to compare *UF** without considering the ergonomic and financial costs of choosing a particular armour section. However, it is wise to bear in mind the constraints even if only as a qualitative discussion from the designer's experience.

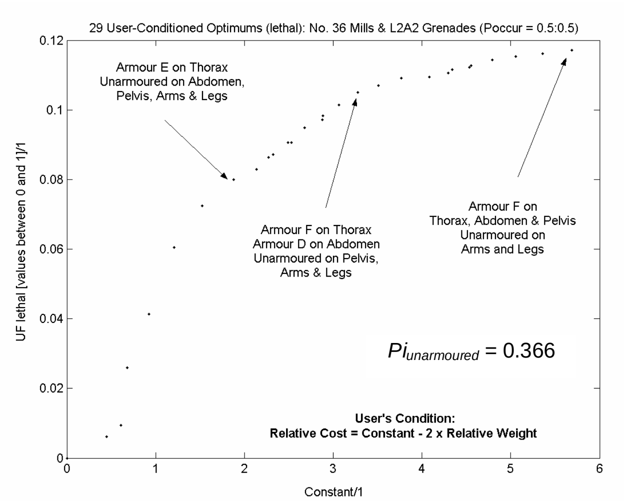
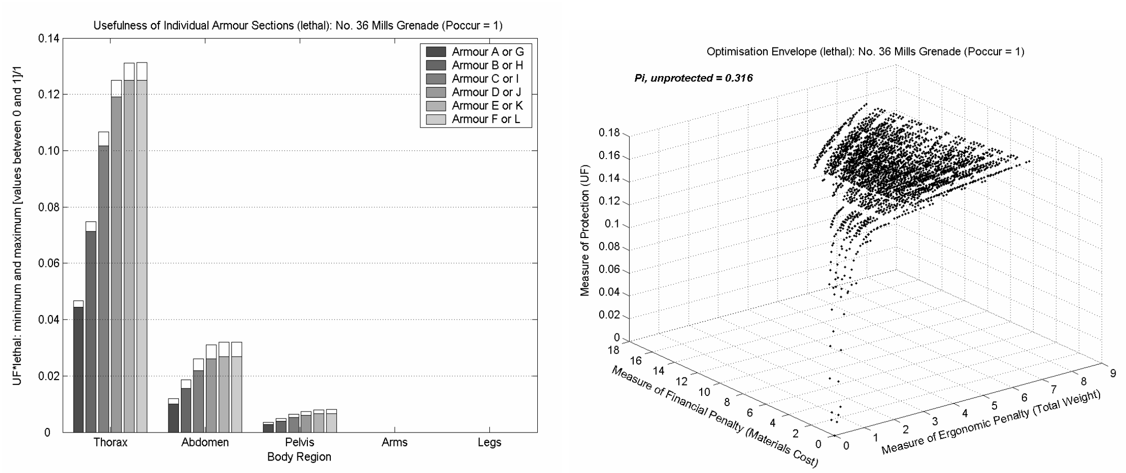


Figure 15: Lethal Constrained Optimisation Envelope for No. 36 Mills (*Poccurrence* = 0.5) & L2A2 (*Poccurrence* = 0.5) Grenades

36 Mills Grenade (Poccurrence=1), Lethal

The graph of *UF** (Figure 16a) presents a small increase in the tolerances associated with armours in the previous two scenarios. It is not possible to identify from this diagram whether or not there is any benefit in using armour F or L rather than E or K. Nevertheless, it is still clear that protecting the thorax, then abdomen, then pelvis must be the priority.



Figures 16a and b: Lethal *UF and Optimisation Envelope for a No. 36 Mills Grenade (*Poccurrence* = 1)**

Figure 16b shows 2865 optimum unbiased armour solutions. The maximum possible protection is estimated to save around 16 percent of lives that would otherwise be lost (UF ≈ 0.16) in this scenario. If *UF* is subtracted from $Pi_{unarmoured}$ then maximum $Pi_{armoured}$ is found to be approximately 0.16. Hence, it is estimated that at least 16 percent of people would die in this scenario. This type of information helps the tactician or strategist decide whether or not their plans are viable and if armour has enough potential benefit.

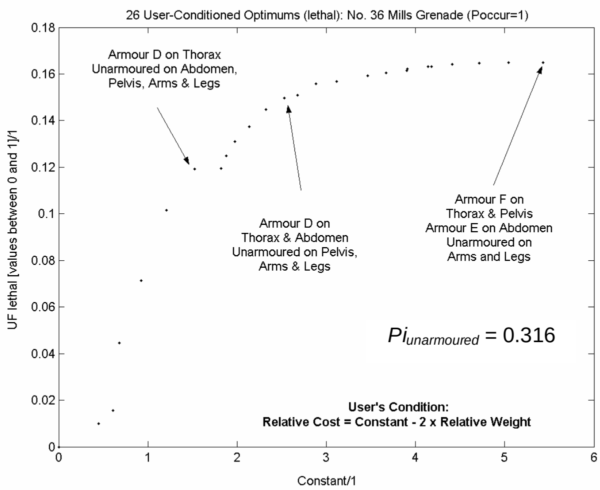
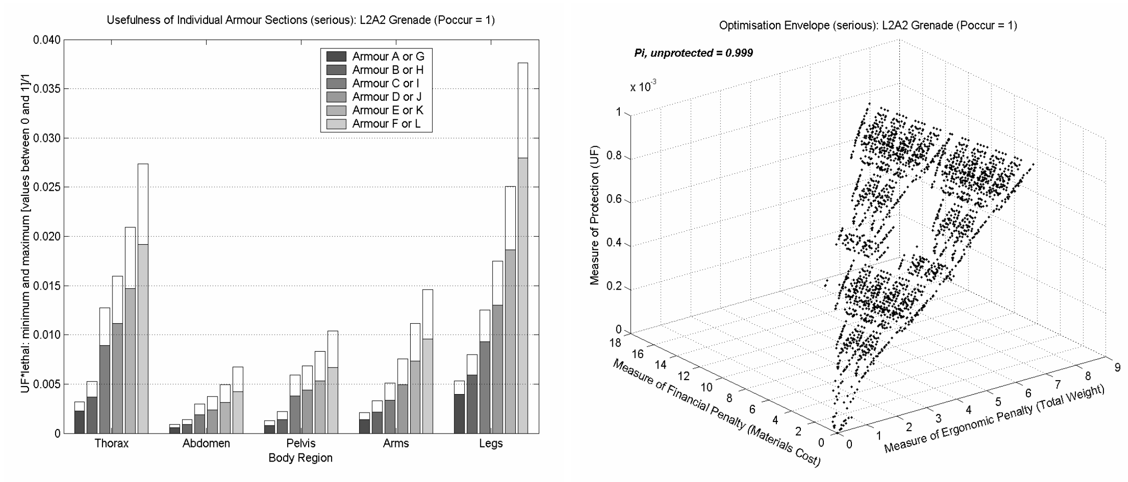


Figure 17: Lethal Constrained Optimisation Envelope for a No. 36 Mills Grenade (*Poccurrence* = 1)

The 26 solutions in the user-constrained subset of optimums (Figure 17) limit the decision maker choice so that they are not overwhelmed by options. Of the three labelled solutions, the first looks particularly interesting because of the acute change in trend gradient. It shows that armour D on the thorax only offers three quarters of the maximum protection for a relatively small weight-cost penalty.

L2A2 Grenade (Poccurrence=1), Serious

Figures 18 a and b show the effect of using the serious incapacitation criteria to assess the L2A2 scenario. The increased tolerances (compared to the lethal scenario) reflects the greater variety of protection possibilities on the rest of the body. *UF** becomes less helpful as the number of potential armour sections that can be combined increases. In Figure 18a for example, it is not possible to accurately distinguish between the benefits of wearing armours E or F (or K or L) on the thorax or E on the legs. Nevertheless, it is still possible to say that in general, for protection at the serious incapacitation level, it is better to armour the legs than the abdomen.



Figures 18a and b: Serious *UF and Optimisation Envelope for an L2A2 Grenade (*Poccurrence* = 1)**

The protection optimisation envelope demonstrates the inclusion of leg and arm injuries through the greater number of points (2112). Moreover, the envelope does not have the sharp rise of the equivalent lethal scenario. Therefore, it is even more helpful if the user restricts the set of optimum solutions

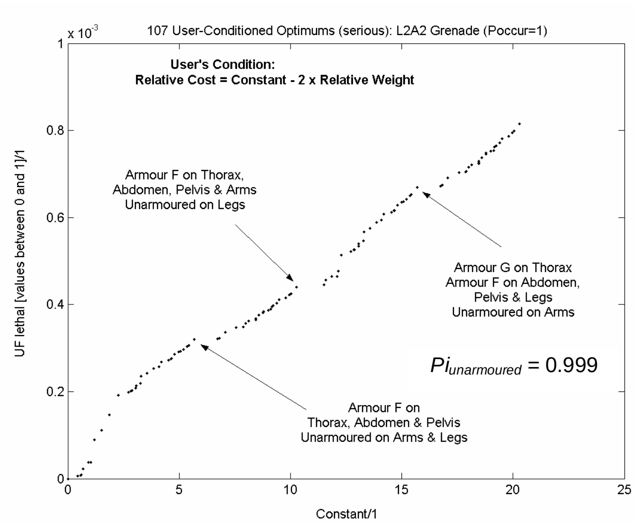
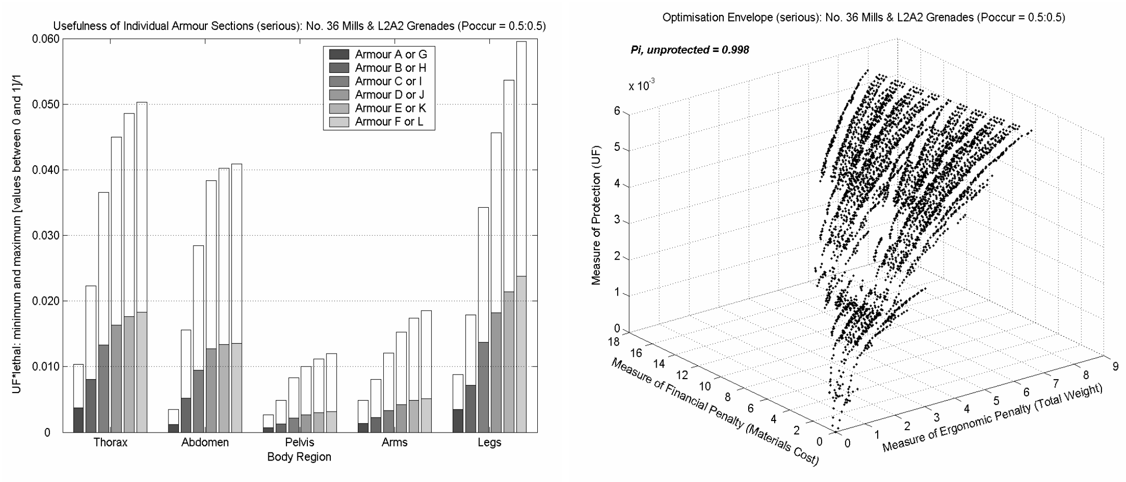


Figure 19: Serious Constrained Optimisation Envelope for an L2A2 Grenade (*Poccurrence* = 1)

The constrained envelope (Figure 19) has 107 points of which three are immediately interesting. The first two show the benefit of wearing armour *a* (cheaper but slightly heavier than armour *b*) on the torso, abdomen, pelvis and legs. It is, perhaps, unsurprising that a single material is found to be useful over large portions of the body. However, the third point demonstrates that some optimum armours may be a combination of different materials as well as protection levels.

The high probability of being incapacitated (0.999 without armour) and the small degree protection that can be afforded (*UF* < 0.01) reflects the danger of being 2m away from a grenade that is guaranteed to detonate. However, the scenarios are theoretical: *Poccurrence* is likely to be much lower. The numerical values in this demonstration are not as important as the general trends.

36 Mills & L2A2 Grenades (Poccurrence=0.5:0.5), Serious



Figures 20a and b: Serious *UF and Optimisation Envelope for No. 36 Mills (*Poccurrence* = 0.5) & L2A2 (*Poccurrence* = 0.5) Grenades**

The values of *UF** in Figure 20a are can only differentiate between the benefits of the three higher levels of armour on the thorax, abdomen and legs compared to the pelvis and arms. The optimisation envelope in Figure 20b is now much more useful than *UF** because all combinations of armour can be considered. 3859 optimum solutions are found for this scenario. This is filtered down to 171 points with the stated user condition (see Figure 21).

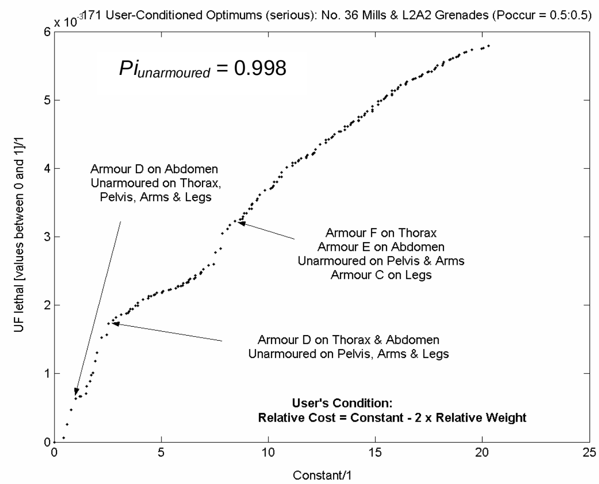
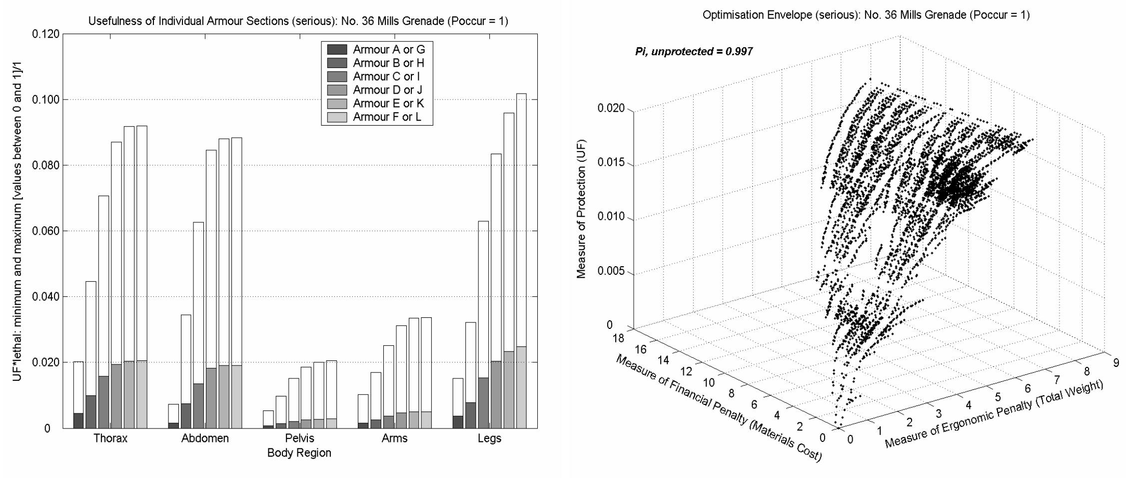


Figure 21: Serious Constrained Optimisation Envelope for No. 36 Mills (*Poccurrence* = 0.5) & L2A2 (*Poccurrence* = 0.5) Grenades

36 Mills Grenade (Poccurrence=1), Serious



Figures 22a and b: Serious *UF and Optimisation Envelope for a No. 36 Mills Grenade (*Poccurrence* = 1)**

Figure 22a show that it is no longer possible to get any useful information about the protection of the system as a whole from a graph of minimum and maximum values of *UF**. This is the result of a relatively wide variety of protection being available over the rest of the body.

Figure 22b presents 4077 optimum points. The bifurcation of solutions is visible in the serious incapacitation scenarios. This is due to the choice of two materials of increasing thickness. It produces a hole in the centre of the envelope where no optimum solutions are possible.

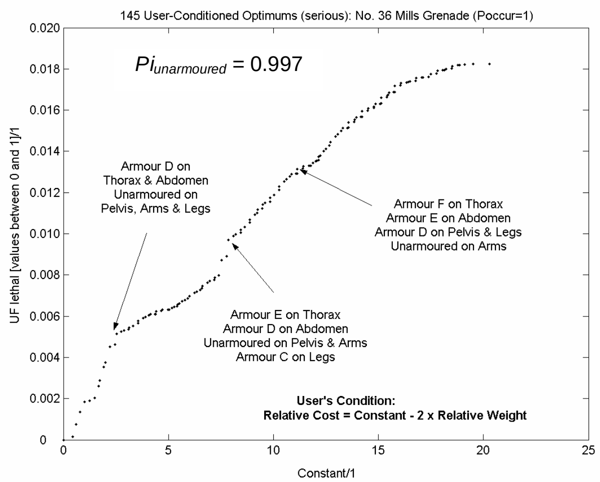


Figure 23: Serious Constrained Optimisation Envelope for a No. 36 Mills Grenade (*Poccurrence* = 1)

The wide variety of possible solutions means that there is no clear distinction between the most useful sections of armour. The individual pieces must be considered as a system in order to reach a sensible design. In Figures 22b and 23, the armour design system outputs are presented in a clear format for the customer to use.

Discussion

Models of personal armour subsystems are often based on approximations, judgement calls and assumptions. One example is that the Kokinakis-Sperrazza model of incapacitation due to fragments means that injuries to the arms and legs are assumed to have no lethal effect. However, rupturing the major blood vessels in the thighs could easily kill a soldier in the battlefield. There is certainly a high degree of professional opinion that goes into models such as these. Nevertheless, they should not be discounted from being used to model the personal armour system. The most important point to note is that models need to 'join together' otherwise they are not helpful for design. The system model must then be continually refined and improved to reflect the growth in knowledge, not just of protection but of ergonomics, finance and the user's needs.

*UF** on its own is not an optimisation tool; otherwise one would simply select the highest level of protection for all areas of the body. It must be traded off against ergonomic and financial penalties. However, the constraints need not be quantified. It is reasonable for the armour designer to liase with the customer and use their own judgement to deselect lesser solutions. Hence, *UF** is part of a 'quick and dirty' tool to enable designers to optimise protection. It is most helpful when there is little variation between the protection offered across the rest of the body. Thus, it is proposed that the use of *UF** should be limited to cases with few different armour sections, such as dividing the body into the three Kokinakis-Sperrazza lethal incapacitation regions.

The protection optimisation envelope, in contrast with *UF**, is an optimisation tool. Its weaknesses are twofold. Firstly, it is limited to models that can be quantified. Secondly, it is time-consuming to construct. Nevertheless, as models and computing continue to improve it is predicted that such quantitative methods will become more prevalent. For example, the authors have already used a different (quicker though less accurate) algorithm that reduces the optimisation time from around 20 computer-days to less than 2. This divides the constraints into a 90×90 mesh, where only the solution with highest value of UF is stored for each cell.

Similar developments and continued improvements should be made to casualty reduction analysis software. It has been demonstrated how CASPER can be modified to calculate the area of coverage, in order to find the total weight and material cost of each armour design. A further development would be to attribute *Pi* to the armour not the area of the body. Moreover, CASPER adding the probability of an event occurring ($P_{occurrence}$) would make it possible to build up dynamic tasks and to study the effects of multiple threats automatically.

Conclusions

1. The armour designer's goal is defined as choosing the right armour (material & construction) for the right area of the body (coverage) at the right time (don or doff), subject to ergonomic and financial constraints.

2. A systems approach to personal armour design is vital in order to understand the benefits or costs of wearing a garment. All measures of success (protection) or constraint (ergonomic performance and financial cost) are relative to the threat, wearer, task and environment. The designer's job is to capture information about the system, predict the best possible solutions and iterate the process to account for any changes as a result of wearing armour. Tools for optimising do not exist to select a single solution but to eliminate those that do not offer the 'best possible protection.'

3. The protection subsystem can be understood as a 5-stage model of occurrence, incidence, resistance, incapacitation and protection with two feedback loops. Any injury mechanism can be applied provided that each stage is understood, even if only as an approximation.

4. Current police body armour design is shown to be a simplified case of the same system as military armour. If it is no longer reasonable to assume that all threats are targeted and can be stopped then the current go-no go testing will not be enough to understand protection.

5. Protection is described by the difference in probability of incapacitation with and without armour (*UF*). This must be calculated for the binomial combination of *Pi* for each event (threat, injury mechanism, body region, etc.), which is integrated over the task duration with respect to time.

6. Feedback in the protection subsystem must be accounted for by iterating the design process otherwise the assessment of the benefits of armour will be wrong.

7. The geometry files in casualty reduction analysis simulations such as CASPER can be modified to calculate the area of coverage for each section of armour. If the materials database is developed to include the areal density and cost per unit area, then the total weight and material cost of each armour design can be assessed automatically.

8. CASPER could be improved by including the probability of an event occurring ($P_{occurrence}$) in order to build up dynamic tasks and to study the effects of multiple threats. Moreover, the individual armour sections should be attributed with the value of *Pi* rather than the body regions.

9. *UF** – the reduction in *Pi* due to wearing a given section of armour – is relatively quick and easy to produce. However, it is only helpful where the difference between maximum and minimum values is small relative to the mean value. This is proof that armour must be understood as part of a system.

10. A further limitation of *UF** is that it is only an estimate of protection. This must be traded-off against ergonomic and financial constraints, which are also dependent on the whole system. It is proposed that *UF** is one measure for 'quick and dirty' optimisation, especially if the constraint measures are qualitative.

11. A protection optimisation envelope – the maximum possible *UF* (usefulness of the whole armour system) for a given combination of ergonomic and financial constraints – can be used for quantitative materials selection. It removes undesirable solutions and provides the user, purchaser and operations analyst with the information necessary to select a particular armour design.

12. The disadvantage of using the protection optimisation envelope is that it is computationally expensive. Nevertheless, it is predicted that as more efficient optimisation algorithms are used, better ergonomic and financial models are produced and computer processor speeds increase this has potential to be an excellent method of selecting armour.

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