The Development of a Warhead into an Integrated Weapon System to Provide an Advanced Battlefield Capability

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Thesis

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Abstract

This thesis addresses the topic of integration of weapons systems into communication networks to provide an advanced battlefield capability, with particular application to air launched and long range crew served weapon systems which may also be vehicle mounted. It considers the use of 'Military off-the-shelf' seeker, navigation and communication systems coupled with a novel tandem warhead system. This combination of 'low risk' technologies and a novel warhead system is intended to demonstrate a greater flexibility in weapon systems which could be exploited to reduce development risk, integration risk, qualification costs and increase target defeat capability across the wider more current target set. The use of a suitable communication and navigation system enabling integration of such a weapon system into a networked force was also investigated.

This thesis is based on one area of research; Multiple Effects Weapons. Research is being undertaken by several nations on Multiple Effects Weapons. The aim of this research is not to provide a one weapon fits all solution, a panacea, the aim is to widen the utility of one system which could be employed in many roles. As yet no warhead system has achieved the types of effects that are being sought, although research and product development – particularly in the United States of America - continues. Therefore the United Kingdom government has sought to understand what technologies would be required to achieve a truly flexible warhead system which would enable defeat of large Main Battle Tanks, heavily armoured Infantry Fighting Vehicles, Soft Skinned Vehicles, infantry and urban structures. To this end numerical

modelling, design and a demonstration programme of a MEW warhead system was performed.

MEW systems are not only reliant on 'Smart' warhead systems, the application of sensors, fuzing and communication systems are crucial to enable suitable employment of a 'one size fits most' approach. The other important sub-systems which provide the link to the battlefield network are also discussed in this thesis, the inclusion of these well developed low risk technologies make it is possible to bring such systems into service in the near term with increased system flexibility. The integration of such a system relies on the current United States Department of Defense procurement strategy which includes development of the Joint Tactical Radio System radio system which will allow Ad-Hoc networking between platforms, weapons systems and commanders.

Airframe and propulsion technologies are not discussed; they are outside of the scope of this thesis. The use of proprietary data from suppliers other than QinetiQ has been avoided as suitable permissions are not in place, this has limited the systems engineering aspects of this thesis to high level block diagrams which provide guidance on integration issues.

Declaration

I, Anthony James Whelan, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed:

Date:

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There are so many people to thank, without whose help this thesis would not have been finished. I would like to thank my old mentor and friend Steve Wheller without his help and confidence in me I wouldn’t have achieved as much as I have. I would also like to thank my family and Victoria who have supported me throughout the writing process. I must also thank Dr Ian Cullis, he has remained patient and has helped me so much in the writing of this thesis, Ian has always had something insightful to say, and has also given me good advice in my career.

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List of Abbreviations

AEFT	Army Evaluation Task Force
AIS	Atlantic Inertial Systems
AJ	Anti-Jamming
AMRAAM	Advanced Medium Range Air-to-Air Missile
AS	Anti-Spoofing
ASM	Anti-Structures munition
ASTOR	Airborne Stand-Off Radar
ATGW	Anti-Tank Guided Weapon
AWDL	Advanced Weapon Data Link
BCU	Battery Coolant Unit
BISA	Battlefield Information System Applications
BRL	Ballistics Research Laboratory
C/A code	Coarse Acquisition code
CAS	Close Air Support
CEP	Circular Error Probability
CHNO	Carbon Hydrogen Nitrogen Oxygen
C4I	Command, Control, Communications, Computers and Intelligence
CIP	Combat Infrastructure Programme
CJ	Chapman Jouget
CMD	Computational Material Dynamics)
CLU	Command Launch Unit
CLU	Container Launcher Unit
CNS	Common Network Services
ComBAT	Common Battlefield Applications Toolset
COMISAF	Commander International Security Assistance Force
CORBA	Common Object Management Request Broker Architecture
COTS	Commercial Off The Shelf
CSSJ	Compact Slow Stretching Jet
DAS	Defensive Aids Suite
DRI	Detect Recognise Identify
DSP	Digital Signal Processing
DoD	Department of Defense
DOSG	Defence Ordnance Safety Group
EBC	Equivalent Bare Charge
EFI	Exploding Foil Initiator
EFP	Explosively Formed Projectile
EPLRS	Enhanced Position Location Reporting System
ERA	Explosive Reactive Armour
ESAU	Electronic Safety and Arming Unit
FCS	Future Combat System
FCS MRAAS	Future Combat Systems Multi-Role Armament and Ammunition System
FOO	Forward Observation Officer
FPA	Focal Plane Array
FPGA	Field Programmable Gate Array

FSU	Former Soviet Union
FTB/MC	Follow Through Bomb/Main Charge
FTG	Follow Through Grenade
GMLRS	Guided Multiple Launch Rocket System
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
HAIPIS	High Assurance IP Interoperability Specification
HCDR	High Capacity Data Radio
HE	High Explosive
HEAT	High Explosive Anti Tank
HESH	High Explosive Squash Head
HKDAS	Hard Kill Defensive Aide Suite
HNS	Hexanitrostilbene
IADS	Integrated Air Defence System
IEEE	Institute of Electrical and Electronic Engineers
IED	Improvised Explosive Device
IFV	Infantry Fighting Vehicle
IGS	Integrated Guidance Systems
IIR	Imaging Infra Red
IM	Insensitive Munition
INFOSEC	Information Security
INS	Inertial Navigation System
IP	Internet Protocol
IPR	Intellectual Property Rights
IPSec	IP Security
ISTAR	Intelligence Surveillance Targeting Acquisition and Reconnaissance
JAGM	Joint Air to Ground Munition
JAN-TE	Joint Airborne Network-Tactical Edge
JBW	JTRS Bowman Waveform
JC-EFP	Jetting Cup Explosively Formed Projectile
JDAM	Joint Direct Attack Munition
J-T	Joule-Thompson
JTAC	Joint Tactical Air Controller
JTRS	Joint Tactical Radio system
KEP	Kenetic Energy Projectile
LADAR	Laser Detection And Ranging
LAFV	Light Armoured Fighting Vehicle
LGB	Laser Guided Bomb
LOS	Line Of Sight
LRIP	Low Rate Initial Production
MAC	Medium Access Control
MAFIA	Modular Advanced Fuze Interface Architecture
M-code	Military code
MANET	Mobile Ad-Hoc Network
MEMS	Micro Electro Mechanical System
MEW	Multiple Effect Weapon
MITL	Man In The Loop
MMW	Millimetric Wave
MoD	Ministry of Defence

MOUT	Military Operations Urban Terrain
MSLS	Multiple Single Level Security
NATO	North Atlantic Treaty Organisation
NDIA	National Defense Industrial Association
NEC	Network Enabled Capability
NEQ	Net Explosive Quantity
NLAW	Next generation Light Anti-armour Weapon
NSA	National Security Agency
OE	Operating Environment
OFDM	Orthogonal Frequency Division Multiplexing
OIF	Operation Iraqi Freedom
P-BISA	Platform Battlefield Information System Application
PETN	Pentaerythritol tetranitrate
PGM	Precision Guided Munition
PGMM	Precision Guided Mortar Munition
PIC	Precision Initiation Coupling
PID	Positive Identification
PPS	Precision Positioning Service
QoS	Quality of service
RAFAR	Raytheon Advanced Frequency Agile Radio
RF	Radio Frequency
RFA	Royal Fleet Auxiliary
RoE	Rules of Engagement
SA	Selective Availability
SACLOS	Semi-Automatic Command Line Of Sight
SAL	Semi Active Laser
SAM	Surface to Air Munition
SAR	Synthetic Aperture Radar
SCA	Software Communications Architecture
SDR	Software Defined Radio
SEM	Scanning Electron Microscope
SEP	Spherical Error Probable
SFF	Small Form Fit
SFM	Sensor Fuzed Muntion
SHAEF	Supreme Headquarter Allied Expeditionary Force
SINCGARS	Single Channel Ground and Airborne Radio System
SiS	Signals in Space
SLAM-ER	Stand-off Land Attack Missile – Expanded Response
SPEAR	Selectable Precision Effects At Range
SPS	Standard Positioning Service
SRW	Soldier Radio Waveform
SSDL	Small Secure Data Link
SSJ	Slow Stretching Jet
SSM	Surface to Surface Missile
SSV	Soft Skinned Vehicle
STA	Surveillance Targeting Acquisition
STANAG	Standardisation Agreement
TACOM-ARDEC	Tank-Automotive And Armaments Command Armament Research Development And Engineering Center

TLAM	Tactical Land Attack Missile
TNT	Trinitrotoluene
TOW	Tube launched Optically tracked Wire guided
TST	Time Sensitive Target
TTP	Techniques Tactics and Procedures
UOR	Urgent Operational Requirement
USMC	United States Marine Corp
USN	United States Navy
UTC	Universal Coordinated Time
WASAG	Westfalische Anhaltische Sprengstoff Actien Gesellschaft
WNW	Wideband Network Waveforms
Y-code	Encrypted P code

Chapter 1
Introduction

This thesis details work undertaken in the field of warhead research and how that work is applicable to advancements in navigation and communications technologies which will allow the integration of weapon systems into communication networks to provide an advanced battlefield capability. The research was focussed on warhead design, modelling, testing and integration into exemplar systems which could provide suitable airframes for future systems. A study of enabling technologies was also undertaken to provide a suitable context for integration into a system which could become a networked node.

This chapter begins by considering the need for MEW (Multiple Effects Weapon) warheads and precision effects, in the context of the current missile systems. The supporting technologies which provide context for the work are then briefly discussed. A literature review is presented to detail historical works that this thesis adds to. The motivation for the research in this thesis is subsequently presented, before briefly detailing the thesis layout.

1.1 The Need for Multi-Role Multi-Platform Weapon

There is a need to simplify the number of weapon system options that are required to prosecute the various tasks that the military have to deal with. These tasks stretch across large scale deliberate intervention operations, through to medium and small scale operations across the planet. This variety of conditions requires an inventory that is able to satisfy every user requirement, however this increases the inventory to levels that make integration extremely complex. A small family of systems that are smart in nature could provide the required effects across both symmetric and asymmetric conditions.

Weapons have grown in complexity, from the unguided bombs of WWII through to the future JAGM (Joint Air to Ground Missile) which is a multi-role, multi-platform missile system [1] and planned to replace the BGM-71 TOW, AGM-114 Hellfire and AGM-65 Maverick missiles. The JAGM will be deployed on the Bradley armoured vehicle, and both the fixed and rotary wing attack craft fleet of the United States armed forces. This progression has shown that the military have moved away from unguided to highly sophisticated weapons that have multiple roles, therefore reducing integration cost, in-service surveillance costs, and logistics costs, and as fewer systems are used to achieve the required military tasks a further cost saving can be made. The movement towards weapons which are more precise in terms of their targeting, and more flexible, in terms of their employment, has been driven by the need to maintain capability whilst decreasing costs, and reducing collateral effects to the minimum possible. To achieve precise effects weapon systems need to be precisely guided; the level of precision required is typically related to the target, warhead type and surrounding environment. To achieve precise guidance communication technologies and on-board navigation equipment, such as GPS, are required. The British MoD (Ministry of Defence) commenced a research programme in the late 1990's, which followed the same principles as the JAGM programme, called SPEAR (Selectable Precision Effects At Range). This programme is discussed in a presentation on the Brimstone missile system which was given by Squadron Leader Jim Mulholland in April 2006 at the Precision Strike Association Annual Programmes Review [2]. The aim of SPEAR is to build on research to improve capability whilst reducing costs.

As previously stated one of the key reasons for fielding a multi-role, multi-platform weapon system is reduction of cost. One of the largest costs outside of the research and development of a weapon system is integration. Integration of a weapon can be a large cost driver for procurement of a new platform, an indication of this is given in the national audit office report [3] which detailed the cost of the integration of the AMRAAM (Advanced Medium Range Air-to-Air Missile) onto the Euro Fighter – Typhoon, quoted as £82M. Elements of this cost would not be repeated if this missile system were to be integrated onto another platform as previous work would have provided much of the data required to solve problems on other platforms such as data transfer (on pylon) and environmental testing. The integration of a common missile which, for example, replaces two missile types may possibly halve integration costs, and also halve in-service surveillance costs and logistics costs (through standardisation of magazine storage and logistic carriage considerations). In addition demonstration costs would be reduced, together with expected cost savings in manufacture (as a single qualified production line would only be required) and qualification. Total through life costs of supporting each of the platforms could thereby be reduced.

In the recent past the world has seen conflict on many fronts. The Middle-East, Africa, the Balkans, and some of the FSU (Former Soviet Union) countries. Some of these conflicts have been symmetric in nature and some have been asymmetric. A symmetric conflict occurs when the opposing forces are equipped with weapons, platforms, logistics and communications of a similar level of technological advancement. The size of the opposing forces should also be similar, e.g. the Iran-Iraq war, which lasted eight years, and the more salient example World War II. Although Great Britain and the United States of America were not initially as well equipped as the axis forces, they did however gain ground quickly through a high level of research and development. In most conventional warfare, the opposing forces deploy force elements of a similar type and the outcome can be predicted by the quantity of the opposing forces or by the quality of the force elements, for example superior command and control or the employment of a well trained army. There are times where this is not true because the composition or strategy of the forces makes it impossible for either side to close in battle with the other.

The term Asymmetric warfare was coined by Andrew J.R. Mack in an article he wrote in the World Politics Journal entitled “Why Big Nations Lose Small Wars” [4]. He identified that Asymmetric warfare occurs when the opposing forces possess resources which differ greatly in terms of technological advancement and indeed in the Tactics, Techniques and Procedures (TTP) that are used. A recent example of asymmetric warfare is the conflict in Afghanistan being fought by the International Security Assistance Force (ISAF) coalition force and the Afghan National Army, with the United States and United Kingdom armed forces leading the coalition. This region has proved to provide significant challenges in the past as the climate and terrain can be exceptionally inhospitable and the native people are exceptionally hardy to such conflicts, as history will testify. The war in Iraq was complex in nature, the initial engagement with Iraqi forces was not wholly of an asymmetric nature. The Iraqi forces were equipped with some Russian equipment including T72 tanks, the republican guard were the best equipped force within the regular Iraqi forces [5]. However the initial attack from coalition forces was an air-strike which used Joint Direct Attack Munition (JDAM) guided bombs, Tomahawk Land Attack Missiles (TLAM), and other guided weapons. The intention of the air strike was to cripple the governmental infrastructure of Baghdad whilst avoiding undue collateral damage.

Following the air strikes Iraqi forces were quickly defeated in the ground campaign which was led by the United States Army and Marine Corp. Following a period of relative quiet an insurgency grew, the insurgency was not coordinated in a sophisticated manner, it was characterised with small groups, fighting with small arms such as the ubiquitous AK-47. These small groups of insurgents were prepared to take risks that seasoned combatants would avoid. These insurgents were initially Iraqi; however with time it was clear that foreign nationals were being recruited into a slowly growing insurgency, this is discussed fully in a report from Kueger on the origins of foreign fighters in Iraq [6]. By July 2003 IED (Improvised Explosive Devices) were being employed by insurgents to disrupt and destroy occupying coalition forces. This tactic has also been employed extensively in Afghanistan, however the insurgency in Afghanistan was also linked to the Taliban forces, a typical Taliban 'section' can be seen in Figure 1.1, which have been attempting to exert their authority on the populous in the face of coalition forces. These combatants offer a challenge to ISAF, their tempo of operations is swift, they offer a low target profile and they stay close to the local civilian population when they feel under threat – this prevents ISAF engaging for fear of collateral damage casualties.

Figure 1.1: Typical Taliban section (image courtesy of Jane's Information Systems)

In the symmetric and asymmetric conflicts discussed, the threats changed measurably, the threats changed from being slower in tempo and predictable to fleeting and unpredictable in nature. The Coalition forces inventory of offensive military equipment did not change to respond to the nature of threat evolution. A key example of this is the Javelin AGTW system, which will be discussed in detail.

Historically air to surface and surface to surface guided weapons have been designed to carry out very specific tasks. On the man portable scale[1] – until recently – this task was to defeat armour capability such as an IFV (Infantry Fighting Vehicle), however new procurements in Israel, the UK and the USA have sought to widen the utility of such weapons. The UK have invested approximately £57M[2], in a new weapon system called the ASM (Anti Structures Munition), discussed at length in Parliamentary proceedings between May 2004 and July 2007 [7] [8] [9]. ASM provides an anti-structure capability with some utility against light armour. An example of a man portable weapon designed for anti-armour defeat is NLAW (Next generation Light Anti-armour Weapon), Figure 1.2, which is a missile equipped with a 'smear compensated' single shaped charge warhead which flies over its target and shoots down to defeat the turret roof, the most vulnerable part of the target.

[1] Typical man portable guided weapon mass is approximately 11kg e.g. NLAW
[2] Consisting of government research, industrial demonstration phase, training and supply of weapons.

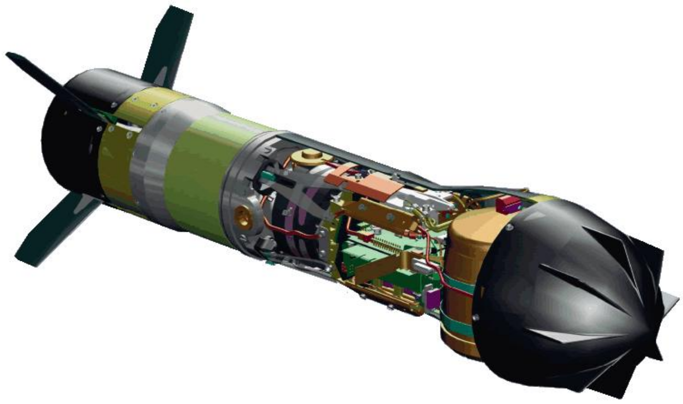

Figure 1.2: Cut-away image – NLAW missile (image courtesy of Saab Bofors Dynamics Sweden)

Air to surface guided weapons have also been designed to carry out specific tasks, an example of this is the Hellfire AGM 114-K, Figure 1.3, which is a tandem shaped charge warhead system is designed specifically to defeat heavily armoured targets, with little or no utility against structural targets or indeed other vehicle targets which would react completely differently from a fully armed MBT when hit.

Figure 1.3: Cut-away image – Hellfire missile (image courtesy of Jane's Information Systems)

War is not simple. Past conflicts have shown that utility is essential. With this in mind, a highly tuned tool can sometimes be used as a blunt instrument. Examples of how these weapons have been used to try to defeat the enemy in a manner they were not designed to, can be gained from looking at the Falklands war which was designated as Operation Corporate.

During Operation Corporate, the first generation Milan ATGW was used extensively. The Milan ATGW was, by current standards, very basic in nature, with the missile wire guided Semi-Automatic Command to Line-Of–Sight (SACLOS), where the gunner guided the missile on to the target by keeping the sight of the command unit on the target during the flight. Milan was designed as a weapon which would be carried by infantry units to defeat heavy and medium armour targets, it was equipped with a single Ø125mm shaped charge, the missile can be seen in Figure 1.4.

Figure 1.4: Milan missile with fins deployed (image courtesy of Jane's Information Systems)

Milan was designed to defeat armoured vehicles, but the Argentine forces were not equipped with armoured vehicles. Milan demonstrated in a short period, between 2nd April – 14th June 1982, that it was capable of being used to support close combat missions where the blast and fragmentation effects were to dominate against the predominately personnel targets.

Several battles took place during Op Corporate; one particularly tough battle, which involved the assault on Wireless ridge, where the British Army deployed Milan was the battle of Mount Longdon. The Argentine troops were well dug-in, the terrain also afforded them extra protection, boulders and rocky outcrops provided ideal cover from which to snipe at advancing British troops. Several Milan rounds were used in that battle, they provided a capability that could be guided on to a position, at range, delivering a significant level of blast in a localised area. One report, detailed in a book about the Falklands War, 3 Para: Mount Longdon – The Bloodiest Battle [10] described how a particularly tough commander, Major Carrizo-Salvadores, abandoned his command bunker only when 'A' Company attacked his position with a Milan missile which impacted rocks approximately 10m behind him. Milan was used in this manner because anti-personnel grenades and small calibre weapons were ineffective due to the well protected positions that the Argentine troops had taken up. Milan attacks provided an alternative to the typical close combat TTPs where in some cases fixed bayonets and small arms were used in one on one combat to clear entrenched Argentine troops. Although the missile was not designed for this purpose it demonstrated some utility which provided a much needed capability that was not present, and aided in defeat of the entrenched forces in the Battle of Mount Longdon.

1.2 Contemporary requirements

The Javelin missile system was used extensively in OIF (Operation Iraqi Freedom) by the US forces; it has also been in service with the British forces from 2005 as detailed in Jane's Defence Weekly [11]. Javelin, Figure 1.5, is an advanced 'Fire and Forget' tandem warhead equipped ATGW, which allows the gunner to move from his position immediately after firing, improving his chances of surviving the engagement.

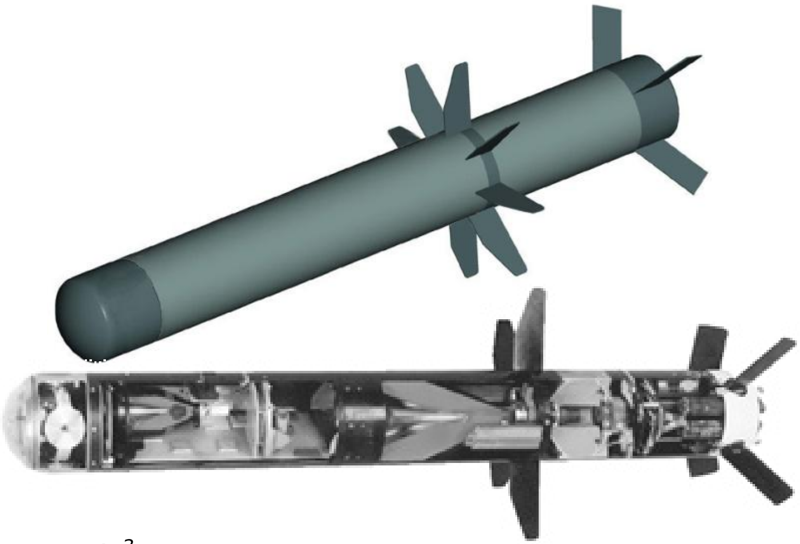

Figure 1.5: Javelin missile[3]

ATGW systems are expressly designed to defeat the heavy armour of MBT targets that are typically moving at speed[4] on roads and across rough terrain; this is discussed further in the background chapter. The missile system uses a CLU (Command Launch Unit) to target the enemy, which is a unit that is detached from the launcher tube following launch of the missile. Following 'Lock-On' the missile is launched, at which point the seeker, equipped with an IIR (Imaging Infra-Red) sensor (allowing the missile to compare the target to the initial instruction from the CLU) locks on to the target, which is between the target 'gates' which are designated by the gunner. The missile is then able to guide itself on to the target following launch. This facility, known as 'lock-on before launch', allows the gunner to move from his position immediately after firing, improving his chances of surviving the engagement should

[3] Top image courtesy of QinetiQ, bottom image courtesy of Jane's Information Systems
[4] Typical off-road velocity of heavy modern MBT is approximately 45km/h

the target be equipped with DAS (Defensive Aides Suite) sensors and countermeasures that would identify a hostile missile launch and instantly instruct the tank crew to respond to the hostile action with a return of fire. MBTs such as the T80U and T90 are equipped with such systems. Engagements using Javelin are shown in Figure 1.6.

Figure 1.6: Javelin missile launched by US Marine Corps soldiers (images courtesy of Raytheon/Lockheed Martin)

Javelin was developed solely to defeat heavy armour on MBTs as shown in Figures 1.7 and 1.8[5], structures and personnel were not considered. The images in Figures 1.7 and 1.8 are taken from a trial performed by the US Government at Redstone Arsenal, Huntsville, Alabama. The trial demonstrated that Javelin is capable of achieving an accurate hit on a MBT at medium range, it also demonstrated that the tandem shaped charge provides a significant defeat capability. However the armour protection on the turret roof of the T72 MBT has not been disclosed, it is therefore not known if the target was equipped with ERA (Explosive Reactive Armour).

[5] Images courtesy of AMRDEC

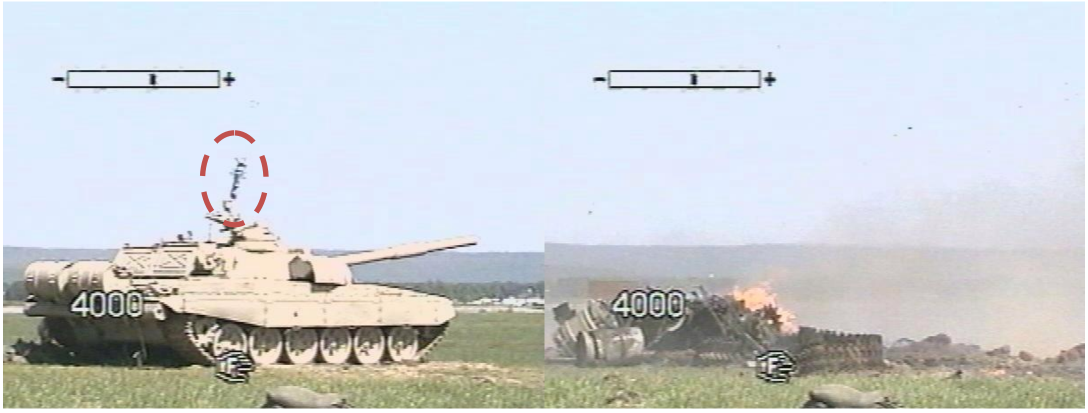

Figure 1.7: Javelin missile in terminal dive phase (circled left) and destroyed T72 following detonation of stored ammunition and propellant (right)

Figure 1.8: Remaining hull (left) turret lifted from vehicle (right)

As can be seen in Figure 1.7, Javelin attacks the turret roof of the MBT, exploiting the weaker, less well armoured area of the target. This defeat mechanism can only be achieved by adopting a high dive attack in the terminal phase of the engagement. This complicates the engineering aspects of the seeker as to maintain target lock the seeker must constantly view the target, since the IIR element has to be gimballed in order to maintain a constant view of the target.

The Javelin missile capability against armoured vehicles is well documented. When used by US Special Forces on 6th April 2003. Javelin destroyed fourteen Iraqi armoured vehicles, two of which were MBTs in the battle of Debecka Pass in Iraq, as discussed in an article in the Boston Globe written by Ross Kerber [12] and an article in the Raytheon Missile System 'Weekly' News [13].

However when used against structural targets[6] Javelin proved to be far less capable. Initially it was reported that the missile would not lock-on when being targeted at buildings, although this should be possible when engaging the direct attack mode if the target is within range. The main issue that makes Javelin less effective against structural targets than might be assumed is the type of warhead system that it is equipped with, a tandem shaped charge warhead system. A shaped charge will only cause damage along its shot line; it will not cause significant levels of damage outside of this zone as the primary purpose of the warhead is to penetrate the thick armour that is typical of MBTs. However some blast and fragmentation effects are generated when the warhead system detonates, which is why Javelin has also been used to 'snipe' at enemy forces as detailed by post operational reports such as the one submitted the Grenadier Guards [14].

When Operation Iraqi Freedom commenced members of the USMC (United States Marine Corps) undertook attacks against several target types with its new Javelin system. However when fired at structural targets very little damage was sustained, several strikes on a target would be required before any success, and in most cases CAS (Close Air Support) was 'called in' to prosecute the target effectively, as discussed in an article in written by Andrew Buncombe in The Independent on

[6] Typically brick built or thin concrete domestic structures were present in Iraq, although occasionally improvised constructions included other materials such as clay bricks

Sunday, 24 March 2003 [15], this was not unexpected as the Army Field Manual on Javelin Medium Anti-Armour Weapon System, detailing the tactical characteristics of Javelin, suggest that effectiveness against structural targets is poor [16].

In an asymmetric conflict the enemy will exhibit completely different tactics and will also be forced to use whatever equipment is available. Consequently in Afghanistan Taliban fighters are limited to using commercially available vehicles such as the ubiquitous Toyota® Hilux® truck, otherwise known as the pick-up truck target. Whilst not being equipped with DAS or heavy armour such vehicles do have the advantage of speed and a small target silhouette, which enhances survivability since such vehicles can be difficult to hit. Crew portable, and even some air launched ATGW systems require a hit or very near miss to ensure a kill on such targets. The main defeat mechanism for such a target is fragmentation and blast, since as previously stated a shaped charge jet will only damage those target elements that are in its path, and with the largest jet particles being only typically Ø40mm[7] damage to a thin armoured vehicle would be restricted to a narrow path around the jet. If a pick-up truck were to be engaged by a Javelin missile whilst moving, a direct hit may be difficult to achieve, it is expected that there would be a high chance of a near miss or miss by several metres. An illustration of the results of a near miss can be seen in the damage to the vehicle pictured in Figure 1.9, the damage was created by detonation of an explosive mass that would be typical of a modern ATGW.

[7] Typical diameter of large shaped charge slug particle or particles from an Explosively Formed Projectile.

Figure 1.9: Blast damage to a First Defense International Group's armoured Ford® Expedition®[8] (image courtesy of Newsbusters)

This demonstrates that in the event of a miss the target will still be severely damaged by the blast and fragmentation of the weapon, but the damage may not be sufficient to defeat the occupants of the vehicle. The image shown in Figure 1.9 is the result of an IED detonation; this is analogous to an engagement from a missile which has missed its target. In the event of a near miss it is likely that the shaped charge would be pointed towards the ground on detonation. Direct attack ATGWs, as opposed to Over-flying Top Attack ATGWs[9], generally adopt a dive angle much shallower than that of Javelin in the terminal phase of target engagement. In the case of this example, therefore, the jet particles from the warhead detonation would miss the target and penetrate the ground under the vehicle, this can be more readily understood in the diagram shown in Figure 1.10.

[8] Damage shown is indicative of fragmentation from a large ATGW (http://newsbusters.org/node/7277)

[9] Over-flying Top Attack ATGWs fly over targets and detonate the warhead(s) above the target

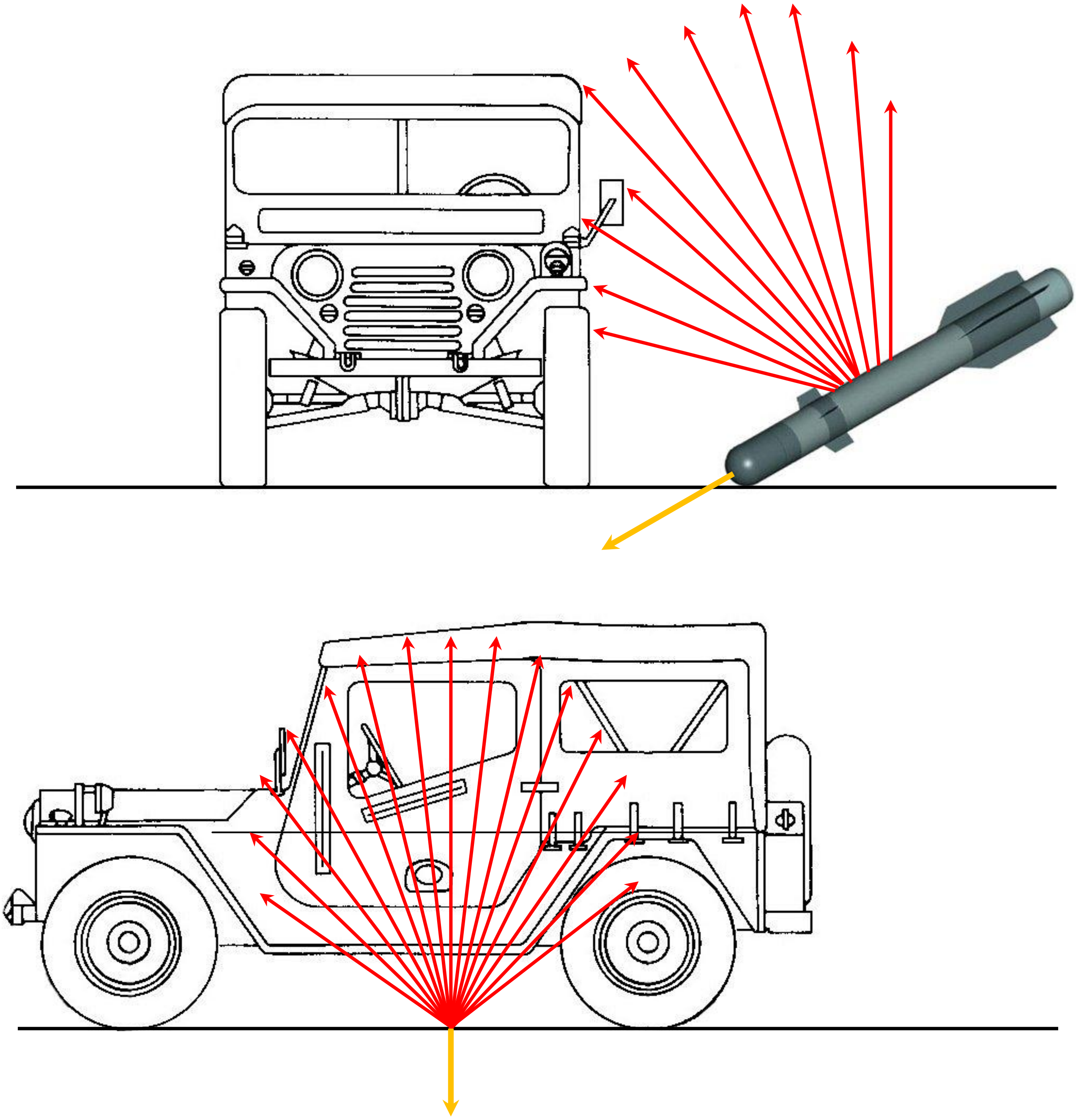

Figure 1.10: Indicative fragmentation pattern from near-miss impact (image of Jeep courtesy of US Army)

As can be seen in Figure 1.10, the main defeat mechanism – shaped charge jet (shown in yellow) – has penetrated the ground under the target; however fragmentation (shown in red) from the main warhead has been projected onto the target. The typical fragmentation from an ATGW relies on casing and fuselage materials, with thin (~2mm) aluminium alloy tubing being a popular material for warhead cases, producing low density high speed fragments which would penetrate the protection offered by soft skinned vehicles.

Any damage sustained by the vehicle shown in Figure 1.10, which may be considered to be a soft skinned vehicle, was due to the combined blast and fragmentation effects from the warhead. The inclusion of a thickened metallic casing around the warhead would enhance the warhead fragmentation characteristics, thereby increasing the probability of incapacitation of the crew of the soft skinned vehicle. This would decrease the blast effect; however blast effects in a free field environment reduce drastically as a function of range[10]. Typically missile systems such as Hellfire use thin aluminium to encase the warhead or warheads (if a tandem system is being used); this does not produce significant fragmentation. However a retrofit is available to improve fragmentation, as a 'bolt-on' and is fitted on top of the outer skin on the warhead, this Tantalum retro fit is shown in Figure 1.11.

Figure 1.11: Hellfire II K variant Tantalum fragmentation overwrap (image courtesy of AMRDEC)

[10] A Blast wave deposits energy into material it passes through, including air. When the blast wave passes through solid material, the deposited energy causes mechanical damage. When it passes through air it grows weaker, blast effects scale with the inverse cube law which relates radius to volume.

As well as being able to defeat softer armoured targets, the ability to defeat the protection afforded by typical urban or rural structures is also a requirement that is not typical of traditional ATGW systems, however it has become of greater interest in the recent past.

1.3 Precision and Avoiding Collateral Damage

Whilst it is possible to combine functions of multiple weapon systems into a single weapon system, it is not necessarily true that the terminal effects can be combined, for example the blast and fragmentation output from a 1000lb bomb cannot be produced by a 50kg missile. However it is possible to provide the effectiveness of a 1000lb bomb with a 50kg weapon. ATGW systems are typically employed to defeat MBTs or other armoured targets, however if the warhead system can be designed to produce enhanced fragmentation, and able to defeat typical urban or municipal structures the need for some bombs can be reduced significantly. A benefit of employing a more precise and smaller weapon system is the reduction in collateral damage; this has become an increasingly important consideration when the mission in Afghanistan is considered. The enemy in Afghanistan employ speed and the ability to exploit the local knowledge. Typically they operate as a small group of individuals as opposed to an army unit. These individuals hide within the community, attack and then disappear back into the community. To be able to respond to this threat a low collateral damage approach is required as ISAF must avoid damaging property and injuring innocent civilians. In his report to the President of the United States, General Stanley A. McChrystal, COMISAF (Commander International Security Assistance Force), his initial assessment in August 2009 [17], stated that there was a need to ensure that collateral damage was kept to an absolute minimum.

"Pre-occupied with protection of our own forces, we have operated in a manner that distances us - physically and psychologically - from the people we seek to protect. In addition, we run the risk of strategic defeat by pursuing tactical wins that cause civilian casualties or unnecessary collateral damage. The insurgents cannot defeat us militarily; but we can defeat ourselves."

This guidance formed the cornerstone of what has become known as the McChrystal doctrine, and as a result ISAF forces adopted a strategy known as 'Courageous Restraint'. With this guidance it was made clear to all of the ISAF coalition that force must only be used as a final option, and when this decision is taken precision strikes were to be the first and only option as opposed to use of general unguided ordnance. With this in mind the need to avoid collateral damage was judged by commanders to be of paramount importance.

An example of this occurred in an attack on a sniper; this was well reported in the Daily Mail newspaper [18]. A Dual Mode Brimstone guided missile was used to attack the sniper who has dug himself into a firing position or "murder hole" in the base of a thick adobe walled compound in the centre of a village in Afghanistan's Helmand Province. Typically a large bomb such as 1,000lb bomb would be used in such a mission; however this would have destroyed the settlement and could have killed other people in the vicinity, thereby creating unwanted collateral damage. Cockpit imagery of the engagement and the eventual strike on the targeted sniper can be seen in Figure 1.12. It is believed that the target was designated by the launch platform, however it is not know how positive identification of the target was carried out, it is assumed that a suitably accurate target coordinate was passed from a forward observer to the pilot.

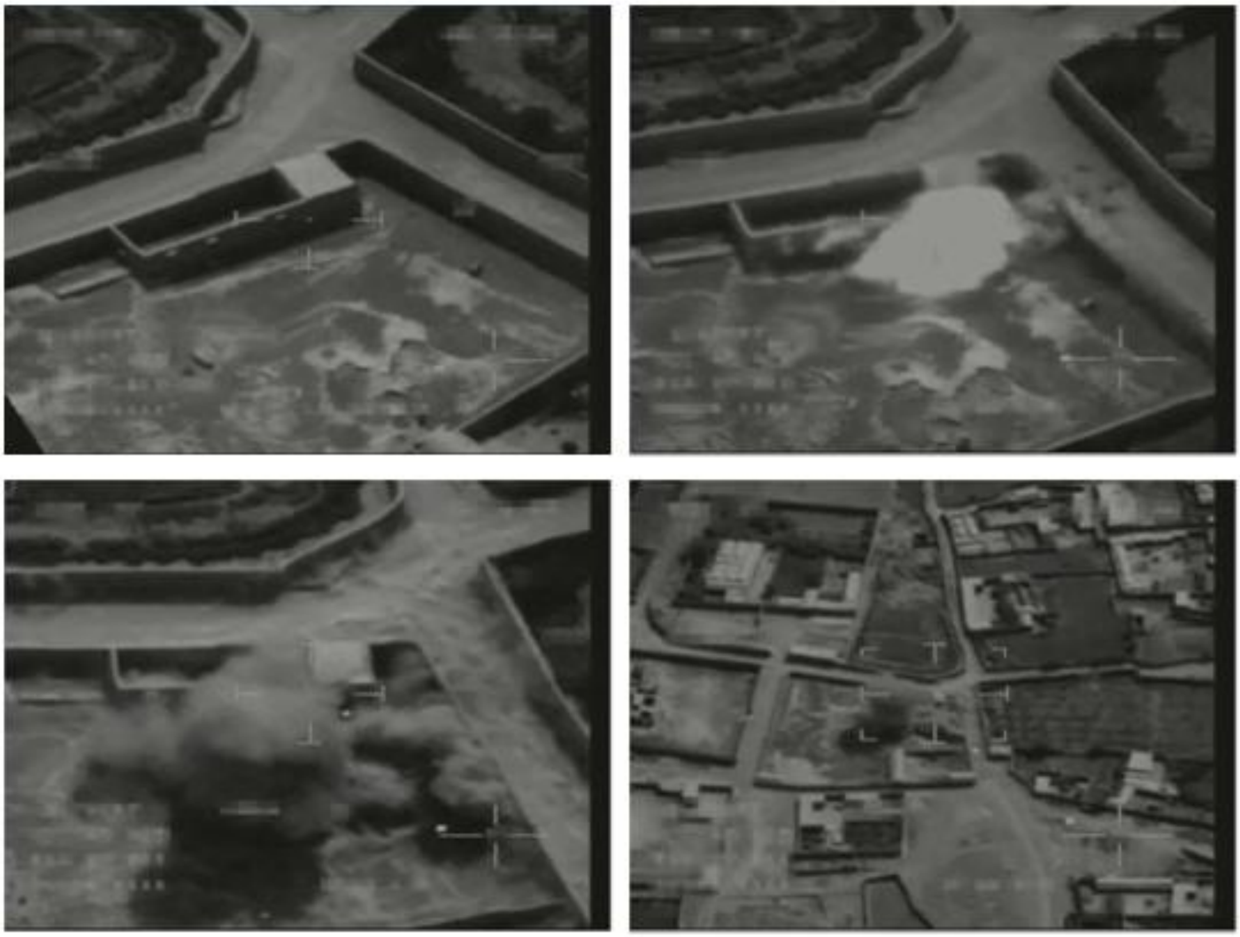

Figure 1.12: Target is acquired (top left), warhead detonates following impact (top right), shock wave passes over wall into street (bottom left), compound wall remains intact (bottom right) - (image courtesy of The Daily Mail newspaper)

The Brimstone warhead is much smaller in comparison to a 1000lb bomb, it therefore only kills the enemy gunman while creating the least damage possible in the rest of the compound. As can be seen in the bottom right image of Figure 1.12 the surrounding streets are untouched as the compound wall has contained most of the fragmentation and debris from the area that was attacked. The images in Figure 1.12 were recorded by the on-board targeting system of a Harrier GR9 which fired the missile, the strike took place in June 2009 and was the first combat use of the Dual Mode Brimstone

The commander of the RAF's Tornado Force serving in Afghanistan, Group Captain Colin Basnett mirrored the will of COMISAF in his assessment of the missile systems capability:

> *"The Dual Mode Seeker Brimstone is an incredibly precise weapon and its introduction into service has significantly increased the capability of the Tornado Force to strike moving or static targets, whilst also reducing the risk of civilian casualties and unwanted damage to property"*

Prior to PGM (Precision Guided Munitions), unguided weapons were extremely inaccurate, so planners compensated for bombing errors by attacking enemy targets with a large strike force carrying heavy bomb loads. During World War II the Air War Plans Division allocated 6,860 bombers to destroy only 154 targets [19]

As depicted in Figure 1.13, the transition to guided weapons has accelerated rapidly since Operation Desert Storm, when unguided weapons were used extensively. With the development of technologies such as LGB (Laser Guided Bomb) and GPS (Global Positioning System) guided weapons expanded the effectiveness of each strike aircraft by reducing the limitations on effectiveness caused by bombing inaccuracies and poor weather restrictions. Advances in precision weapons technology were apparent during recent combat operations in Afghanistan and Iraq. Both operations are regarded as an unprecedented demonstration of air combat power.

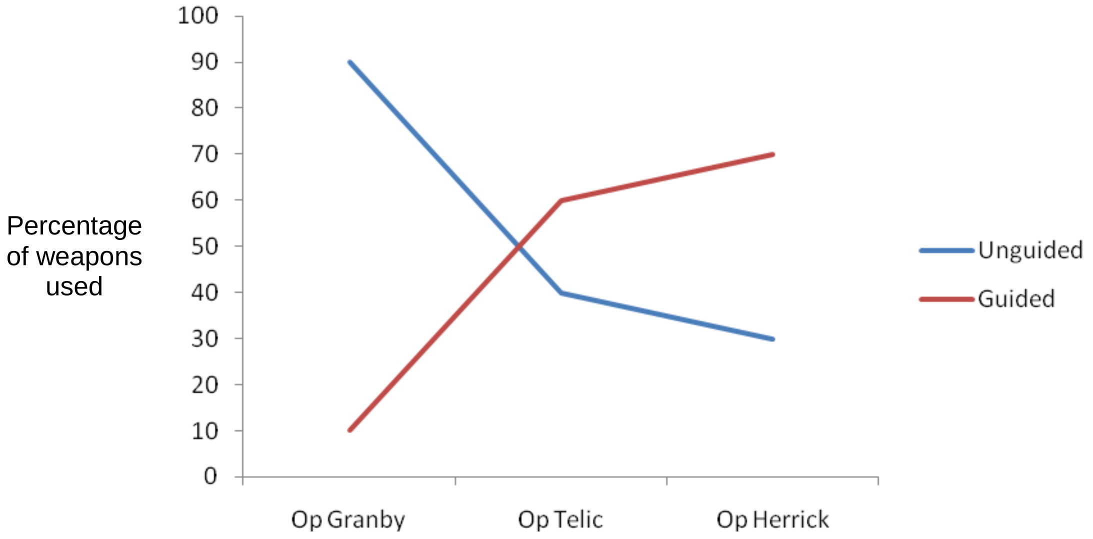

Figure 1.13: Percentage of guided and unguided munitions in recent NATO coalition operations

As a result of this accuracy has improved, as describe in a paper published by Hallioin of the Royal Australian Air Force [20], which details the increase in accuracy of weapons over the last seventy years through to the operations in Afghanistan, Table 1.1.

Conflict	Circular Error Probability (m)
WWII	1000
Korea	330
Vietnam	130
Afghanistan	<10

Table 1.1: Accuracy of munition delivery between WWII and Op Herrick (Afghanistan)

Analysis undertaken by the SHAEF (Supreme Headquarter Allied Expeditionary Force) Bombing Analysis Unit in Report No 10 showed that during WWII the allies required 610 tons of bombs to destroy one primary battery [21]. This illustrates the need to employ precision, as the resources required to launch such a mass of weapons can be prohibitively expensive and the risk of collateral damage is exceptionally high. According to a DOD report, following the operations in Kosovo [22] the use of guided munitions was preferred as 70% of the time targets were obscured by cloud, making attacks with unguided munitions very difficult, and as a SAM (Surface to Air Missile) threat was in theatre there was little option but to carry out missions from high altitude. This demonstrated to NATO (North Atlantic Treaty Organisation) that the use of guided munitions allows accurate strikes to be achieved in almost any weather conditions.

A major part of avoiding collateral damage is the unplanned detonation of explosive stores. To mitigate against this it is the mandated requirement to achieve high IM (Insensitive Munitions) compliancy; IM has been an issue of concern across NATO for many years. IM compliancy requires that any weapon system be able to pass a set of tests which are mandated in NATO STANAG 4439 Policy for Introduction and Assessment of Insensitive Munitions [23],the French have equivalent tests known as MURAT (Munition à Risque Atténué) these tests replicate the violent environment that a weapon system may encounter, they are listed below:

- STANAG 4240 Fast Heating – representing fire in the immediate vicinity of the weapon
- STANAG 4382 Slow Heating – representing fire in a neighbouring magazine
- STANAG 4241 Bullet Impact – representing attack from large calibre small arms
- STANAG 4496 Fragment Impact - representing impact from a large high speed bomb fragment
- STANAG 4526 Shaped Charge Jet Impact – representing attack from a weapon equipped with a shaped charge
- STANAG 4396 Sympathetic Reaction – representing detonation of a similar store which is adjacent to the store being tested

To achieve full compliancy the tested munition will ideally pass each one of the tests with a type V reaction (no reaction) however a type IV (ignition and burning with non-violent pressure release) reaction may be acceptable upon examination of the test results, with type III (ignition and rapid burning) reaction from shaped charge attack also being accepted. Achieving high compliancy with these tests is extremely important, since it may save lives and equipment. An example of what can happen is shown in Figure 1.14, which shows RFA (Royal Fleet Auxiliary) Sir Galahad, which was attacked on 8th June 1982 off Port Pleasant, Fitzroy, Falkland Islands, after attack by Argentine aircraft (three A4-B Skyhawks) which dropped two bombs onto her hull. Another well known example of naval vulnerability to this type of threat is USS Forrestal which was nearly destroyed during the war in Vietnam.

Figure 1.14: Remains of RFA Sir Galahad (image courtesy of the United Kingdom Royal Air Force)

Following impact of the bombs (there is some argument over whether or not the bombs detonated or deflagrated) forty eight Welsh Guards and ship's crew died. The damaged caused to the ship and the numbers of casualties might have been lessened if the ammunition on board were less sensitive to initiation from unplanned ignition sources such as fragment impact or fast heating. This type of incident has driven a requirement to reduce the sensitiveness of all ammunition across NATO.

1.4 Supporting Technologies

Communication, seekers and navigation technologies all provide essential sub-systems in a flexible capability which would deliver a MEW warhead system to its target.

1.4.1 Communication technologies

Communication technologies have greatly augmented military capability; an example of this is the adoption of Morse code in Varna during the Crimean War in 1854. Laying this sub-sea telegraph system enabled British and French field commanders to communicate instantly with one another and with their respective headquarters in London and Paris. Morse code was also used extensively in the American Civil War, and the Spanish-American War found the first use of telegraphy for newspaper correspondents (1898). The first military use for radio telegraphy was during the Russo-Japanese War in 1904/5. However digital communications now provide the backbone of the military communication network.

The ability to guide weapons on to a target has been used for some years; wire guided weapons provided a simple means of control which would enable the operator to guide the weapon onto the target. However this technology was very limited. Range was the primary constraint with these systems, only a limited spool of wire could be carried to support the missile, for example the BGM-71 TOW (Tube launched Optically tracked Wire guided) missile system is restricted to a range of 3.8 km. This approach was not acceptable for air launched weapons, to ensure accurate guidance on to targets SAL (Semi Active Laser) was widely used; this has the disadvantage of requiring designation of the target with a laser. The target may be self designated by the launch platform or designated by a third party on the ground such as a FOO (Forward Observation Officer). Both approaches will provide a high probability of hit on slow moving targets although this probability drops significantly when fast moving manoeuvring targets (>50kph) are engaged as reacting to target movement can be extremely difficult, particularly if control surfaces are limited in size.

When a FOO cannot designate a target, i.e. the FOO may be under directed heavy fire from a sniper, there may be a need to guide the missile through direct radio link, from either the launch platform or another party, perhaps an ISTAR (Intelligence Surveillance Targeting Acquisition and Reconnaissance) asset such as ASTOR (Airborne Stand-Off Radar). There are two further advantages through the inclusion of a radio communication system that would allow a missile to be guided to a new co-ordinate. Firstly the target may be in an area where the risk of collateral damage may increase quickly, therefore an ability to destroy or reroute to an area where the missile may impact dead ground would mitigate against this risk. Secondly the ability to quickly switch the target designation to another much more attractive target, such as a command element, would provide an ability to attack TST (Time Sensitive Targets) in a complex changing battlefield environment.

The importance of communication has been discussed and, the UK forces have moved on to embrace modern communications technologies. The UK forces have migrated to the Bowman radio system, part of which is capable of using WNW (Wideband Network Waveforms). A WNW service can only be hosted on a form of SDR (Software Defined Radio) as such an approach is able to cope with the variety of waveforms required to service the varying requirements on the battlefield. WNW is important as it supports the use of IP based communications in a MANET (Mobile Ad-Hoc Network), this enables not only voice but also data communication. An SDR platform can be considered to be similar to a Personal Computer which is merely a tool which provides an infrastructure upon which applications can be loaded; SDR has several benefits over normal radio systems.

- Multi-Band – The ability for a radio to be configured to work in any one of a number of communications bands.
- Multi-Mode – The ability for a single radio to work in a number of different operating modes e.g. Bowman, Link-16 etc.
- Multi-Channel – The ability to support multiple simultaneous communication channels.
- Enhanced Capability – SDR has the capability of being easily updated through software patches, this allows greater flexibility e.g. protocols and cryptographic algorithms can be updated.
- Size, Weight and Power Reduction – A single SDR is capable of hosting many waveforms, i.e. many parties can communicate to a single radio system even though they are operating with a fixed waveform.

Suitable SDR hardware would allow control of network assets (such as a missile) to be prioritised by the mission commander, i.e. suitable permissions would be attributed to the various force elements.

1.4.2 **Seeker technologies**

The seeker is a key component in a missile system, it is a transducer that allows the missile to lock on to its target. There are several technologies available:

- IIR - Infra-Red
- MMW - Millimetric Wave
- SAL - Semi-Active Laser
- LADAR – Laser Detection and Ranging
- SAR - Synthetic Aperture Radar

The selection of a seeker is linked to the mass and volume constraints, the environments that the system will be operating in, the targets to be engaged, and the cost.

1.4.3 **Guidance and Navigation technologies**

Guidance and navigation technologies have been dramatically influenced by the advent of the GPS (Global Positioning System) as a back-up to an INS (Inertial Navigation System). Dr Carlo Popp [24] states:

> *"There are few guided munitions today that do not use GPS either as a primary or backup navigational reference. As the cost of GPS receivers declines, fewer and fewer munitions will exist without GPS capability"*

GPS has allowed accuracy to increase significantly; new GPS technologies have become hardened to jamming, although coupling with INS provides some redundancy where highly sophisticated enemies are able to deny GPS service.

1.5 Literature Survey

This section lists the significant entries in the open literature that relate to this thesis on the following topics:

- Precision Guided Munitions – employing multiple seeker detectors and navigation systems
- Warheads – exhibiting multiple effects
- Anti Structures Warhead Systems

This review aims to present work undertaken by other individuals, private concerns and state sponsored agencies. The work will be discussed with a view to understanding where common and unique elements exist. Any variations in assumptions and results will be analysed with conclusions being drawn. There are some limitations to the material that has been published on this subject; detail will be limited as a result of security classification and the commercial need for companies to ensure that their IPR (Intellectual Property Rights) are guarded from exploitation where patents are not in place. Therefore the bulk of the material that has been reviewed is not of the same level of detail as the research described in this thesis. This survey highlights the body of past knowledge that informs this thesis, and also highlights the gaps in knowledge that exist that this thesis seeks to address.

1.5.1 **Network Enabled Precision Guided Munitions - Benjamin F. Koudelka, Jr., Major, USAF, Center for Strategy and Technology, Air War College, Air University, Nov 2005**

In his work, Major Koudelka discusses how the evolution of munitions has moved on from WWII. Koudelka quotes that during WWII the Air War Plans Division allocated 6,860 bombers to destroy 154 targets whereas the approach now is to provide one target kill per munition launched. Koudelka also provided statistics on the use of unguided vs guided weapons systems from Op Desert Storm through to Op Iraqi Freedom; these are shown in Figure 1.15.

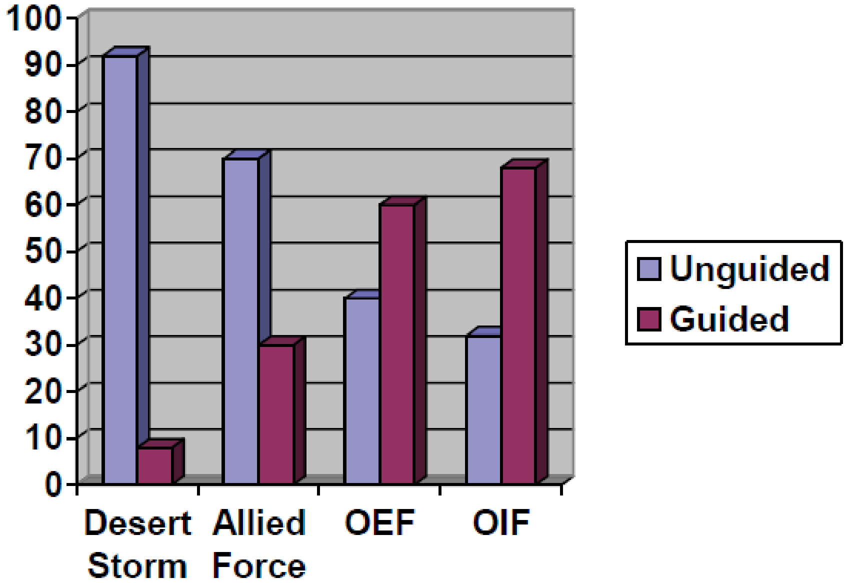

Figure 1.15: Percentage of guided vs. unguided weapons used in recent US operations

As can be seen in Figure 1.15; the use of PGMs has increased significantly; this is a capability that has been exploited further in recent years because of the will to increase effectiveness and to reduce fratricides. Koudelka refers to the PGMs as being capable of achieving a CEP of 9.9' he also describes them as being systems which have a MITL (Man In The Loop) or autonomous control throughout the flight of the weapon. He also states that the development of these weapons in the 1990s was driven by the need to engage targets in all weather conditions, made possible through the development of the GPS constellation. Koudelka also states that Time Sensitive Targets provide a challenge to PGMs that are reliant only on GPS coordinates as these targets may move before the weapon can achieve its aim, whereas laser guidance improves the probability of hit on such targets. The ideal, however, would be an updated guidance solution which can be fed directly to the munition in flight, Figure 1.16.

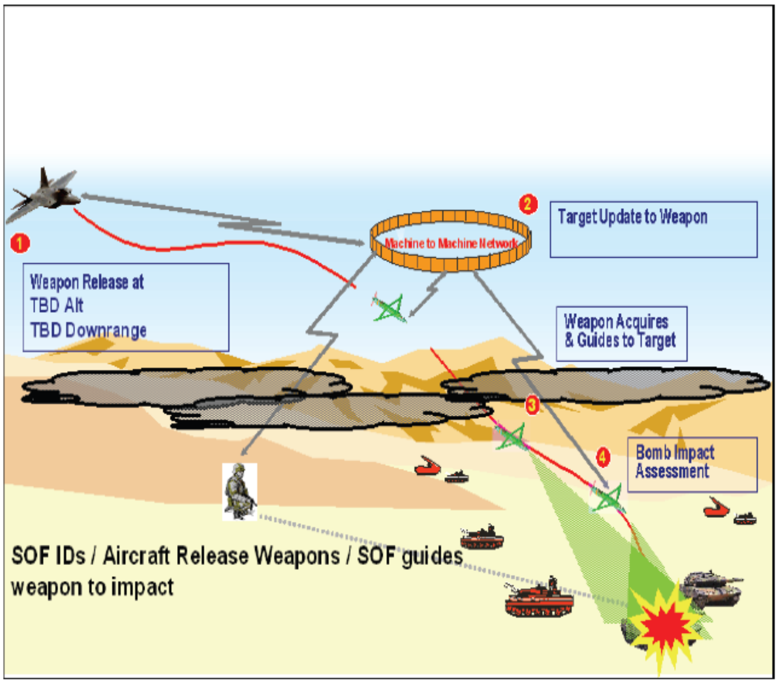

Figure 1.16: Close Air Support attack of prioritised target

In Figure 1.16 the JTAC (Joint Tactical Air Controller) fixes, tracks, and targets an enemy tank moving toward friendly forces and then tasks an on-call F/A-22 equipped with network enabled PGMs. After release of the weapon however it is clear that blue forces may be too close to the target which was originally designated. It is therefore necessary to re-task the munition to a new target or to fly it into an area where it will pose no danger to friendly forces or civilians. To achieve this, the JTAC (or in the UK the Forward Air Controller) would provide a target update to the munition. This is made possible by the inclusion of communications and navigation technologies within the munition.

Koudelka's paper provides a basis for the work undertaken in this thesis; it provides a high level brief on what is required for PGMs that could achieve high accuracy as a result of being a network node.

1.5.2 Dual Mode Warhead Technology for Future Smart Munitions, Mr. David Bender[1], Mr. Richard Fong[1], Mr. William Ng[1] and Mr. Bernard Rice[1], 19th International Symposium of Ballistics, Interlaken, Switzerland, 7–11 May 2001

This symposium paper details work undertaken by TACOM-ARDEC (Tank-Automotive And Armaments Command Armament Research Development And Engineering Center) on the subject of multimode warhead systems. The authors discussed the advance in sensor technologies in SFM (Sensor Fuzed Munitions), and how EFP (Explosively Formed Projectile) warheads may not necessarily be the most effective defeat mechanism for all targets encountered. The author's solution to this was to develop a multimode warhead which would employ a smart initiation system. The smart initiation system would be employed in several modes, allowing a standard EFP projectile to produced, or a stretched EFP, or a flatter Misznay Schardin[11] projectile or multiple fragments. An illustration of this can be seen in Figure 1.17. Only the first two modes were discussed in this paper.

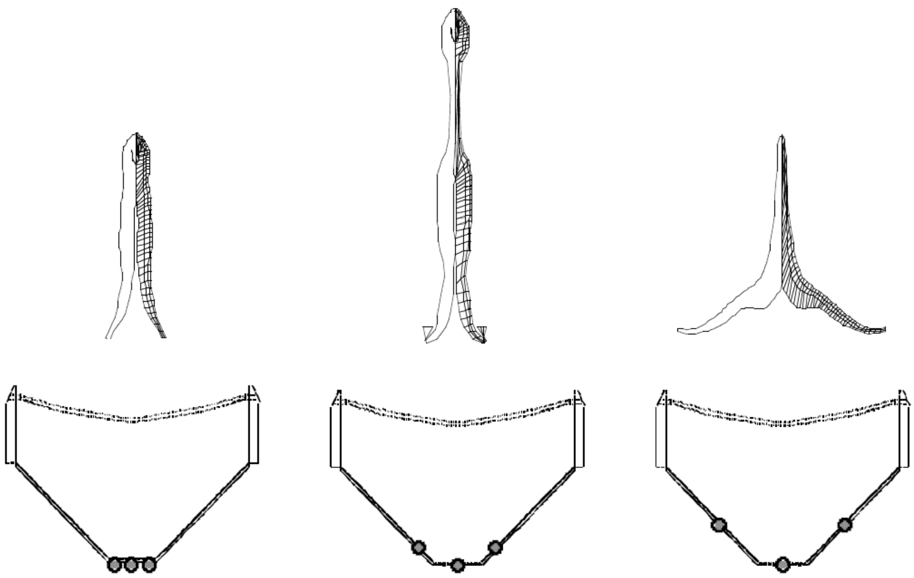

Figure 1.17: Multiple initiation mode projectiles

[11] This effect was observed by explosive experts József Misznay (Hungarian), and Hubert Schardin (German), who sought to develop anti-tank mines for Nazi Germany. They discovered that a large flat projectile would result if a flat detonation wave impacted a shallow dish liner.

This work demonstrated good use of a simple method to broaden the applicability to a single warhead design. It appears that the base warhead design used in this research study was derived from the TOW2B warhead system. The initiation technology was not well described; it is well known that initiation of multiple points from one detonator source, or from several detonators can result in asymmetry. However it is also well known, in the warheads research community, that the most effective way to control such an arrangement is to use EFI (Explosive Foil Initiator), such as the Perkins Elmer blue chip detonator which is housed in a T0-5 transistor casing. As a result of using this approach the safety and arming unit complexity increases with the number of options for warhead initiation. This work has demonstrated that the addition of a complex initiation system to a simple warhead system can yield multiple outputs which will broaden the effective use of the system it is used in.

The resulting outputs from the varying initiation points can be seen in Figure 1.18, as well as varying initiation points, alteration to the liner profile were made.

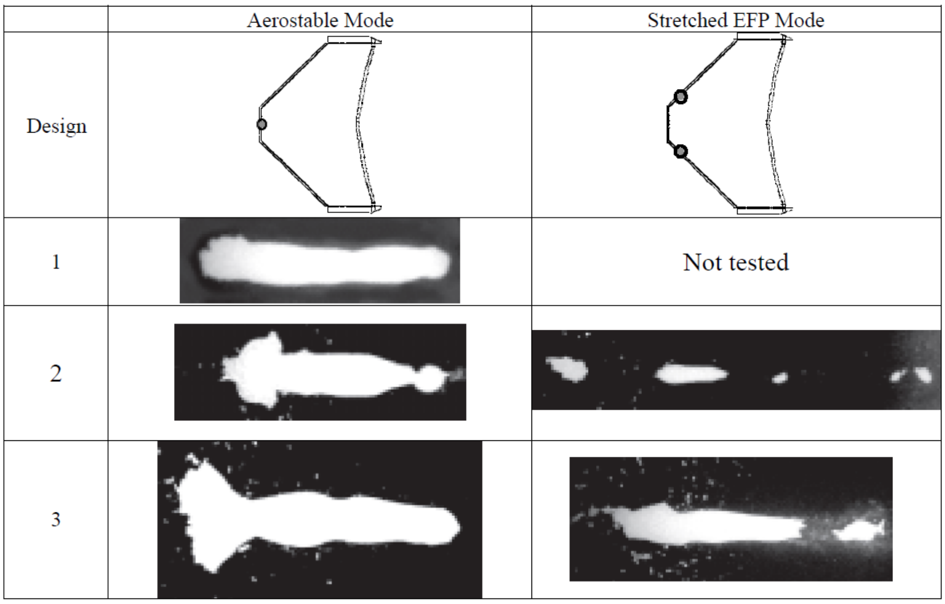

Figure 1.18: Radiography of multimode experiments

Whilst it was possible to demonstrate some control over projectile formation in the normal EFP and stretched EFP modes, Fong *et al* did not demonstrate generation of a Miznay Shardin projectile, although this did not appear to be in the scope of the reported work.

This work was considered as a possible avenue for research to improve the performance of the precursor warhead in the multiple effects warhead system. However the cost of implementing such a technology would outweigh the benefits of being able to generate varying outputs. One of the main benefits of the selected precursor warhead technology in the research that supports this thesis, the CSSJ (Compact Slow Stretching Jet) was the low cost and relatively simple design approach. The CSSJ is capable of defeating several target types at stand-offs that can be achieved by typical guided missile systems. The only benefit that the multi mode warhead approach does offer is the ability to penetrate through seeker clutter, and achieve some effect against the target. As discussed in the thesis a simple approach which may reduce the effect of the seeker components on the precursor warhead is to integrate the warhead system into the seeker elements, thereby leaving a clear path for the projectile to pass through before impacting the target.

1.5.3 Penetrator / Shaped Charge System Part II: Influence of Design Parameters, Werner Arnold[1], Ernst Rottenkolber[2], 23rd International Symposium on Ballistics Tarragona, Spain 16-20 April 2007

This symposium paper details work undertaken by MBDA Deutschland (formerly TDW) on the subject of a multipurpose warhead system. The authors discussed the change in emphasis from defeat of MBTs as being of high importance, to the defeat of structural targets. The paper states that the ability to defeat MBTs is maintained by the proposed design, but that the ability to defeat a variety of targets through blast and fragmentation has resulted as a benefit of design changes to a baseline warhead. The use of an insensitive munitions approach was not discussed in the paper; it is therefore assumed that it was not a consideration. The authors described a warhead, as shown in Figure 1.19, that is the combination of a high performance shaped charge and an FTB.

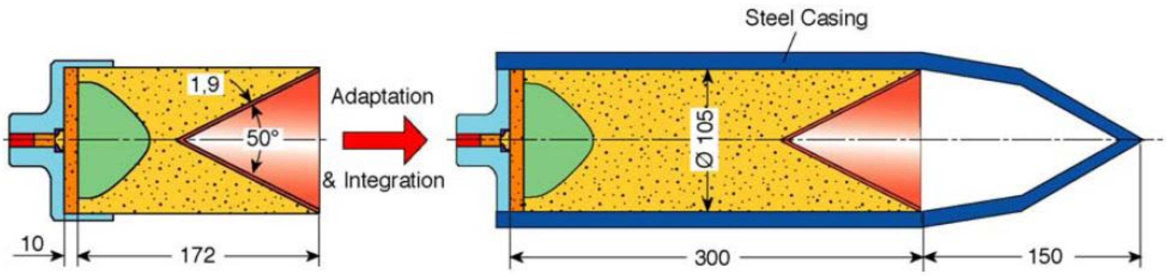

Figure 1.19: Adaptation and integration process of baseline SC into an FTB casing

Trials were undertaken by MBDA to investigate the influence that casing thickness would have over a shaped charge jet. Four designs were fired, with the variation in thickness of case being 5mm and 10mm. Radiography of the firings was undertaken allowing analysis of the jets, and measurement of jet velocity to be obtained, the radiograph can be seen in Figure 1.20.

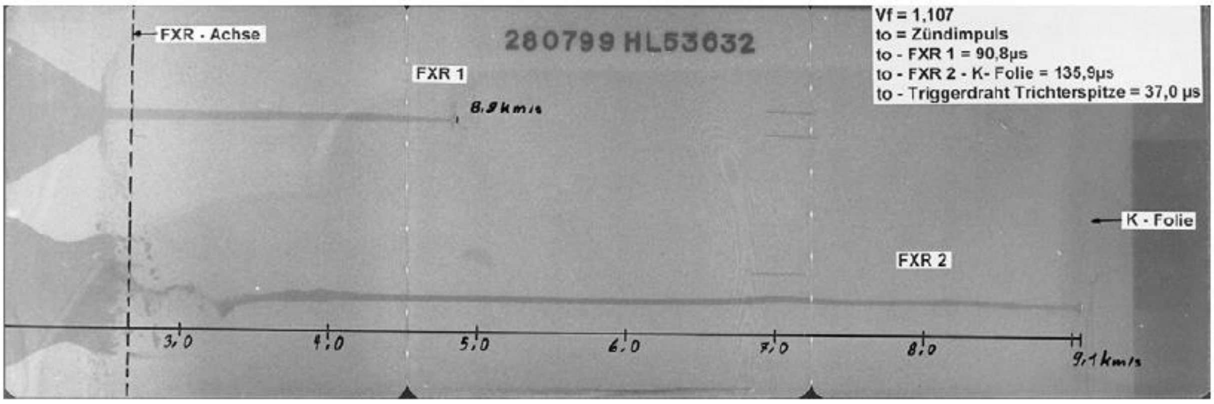

Figure 1.20: Radiography of jet perforating the warhead casing

It is clear that there are several perturbations along the length of the shaped charge jet, and this point was discussed in the paper along with a reduction in tip velocity, and attributed to being the cause of a reduction in armour penetration. There was no analysis as to why the jet was perturbed, this is similar in nature to the effects seen in the jet produced by the main warhead design, the FTB/MC (Follow Through Bomb / Main Charge) which was derived following research which supports this thesis, although it was clear that the inaccuracies in the machining of the wave-shaper cavity probably provided the greatest level of asymmetry, resulting in jet curvature.

The authors undertook a simple design and firing programme, exploring various options to ensure the highest level of shaped charge penetration. The warhead design was not claimed to be part of a system i.e. a guided weapon, but as a single warhead that would replace a tandem system in attack of all types of targets. The utility against structural targets cannot be assessed, however the performance against heavily armoured targets such as BMP 3 or T80-U would require a high performance precursor warhead which would defeat or disrupt any appliqué[12] armour. As previously mentioned the use of an insensitive explosive was not stated in the paper, it is therefore assumed that this was avoided as such materials can be difficult to integrate into precision shaped charges.

This approach is not identical to that taken in this thesis, the authors have suggested that the system demonstrated, could replace a tandem warhead system. This may be linked to the inclusion of a very thick case, which removes mass which could be made available for a precursor warhead. The work in this thesis describes a system which comprises of a tandem system, considered essential for attacking a

[12] Appliqué armours are add on armour systems that are applied to armoured vehicles to improve protection against attack from Kinetic Energy penetrators and Chemical Energy warhead systems.

wide spectrum of targets, particularly when appliqué and thick structural targets are encountered.

1.5.4 Warhead Against Fortified or Armoured Targets, Particularly for Damaging Runways, Roadway Pavings, Bunker Walls or the Like, Gerd Kellner and Karl Rudolf, US Patent 4967666, Nov 6th 1990.

This patent was originally registered by Messerschmitt-Bölkow-Blohm GmbH in 1980. The patent describes how the warhead system is designed to defeat a large variety of targets including armour and structural targets. The warhead system can be seen in Figure 1.21.

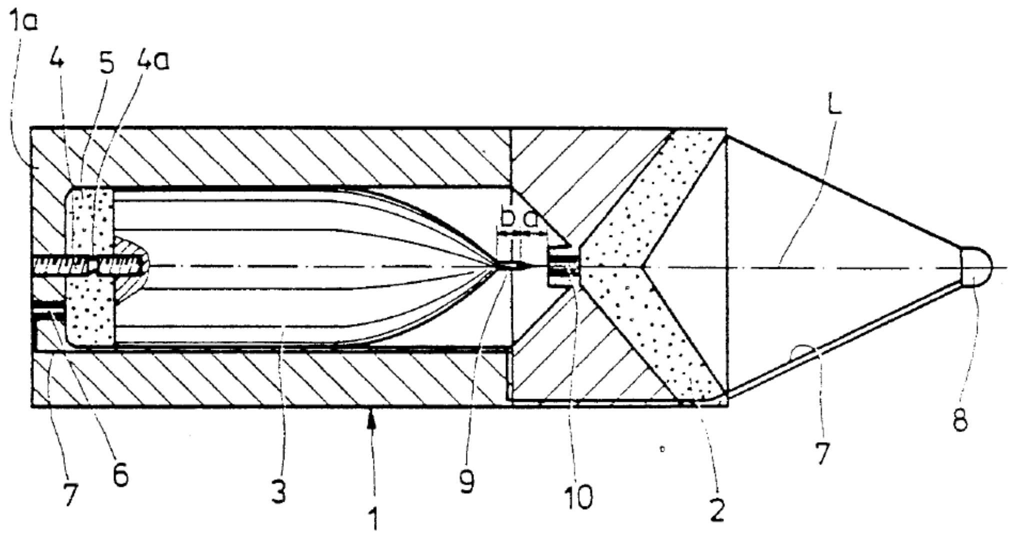

Figure 1.21: Tandem multiple effects warhead system

This warhead system comprises of a precursor warhead which is designed to perforate armour and structural targets. During detonation of the precursor warhead a propellant charge towards the rear of the rear warhead (marked 5) initiates rapidly propelling the rear warhead forwards. The patents claims that whilst the precursor produces a large hole in the targets, that the rear charge is propelled through the hole created by the precursor. This allows the rear charge to be emplaced within the target. This approach is similar to anti-runway mine systems such as JP-233 which contained thirty SG-357 runway cratering bomblets each weighing 50lbs.

This patent demonstrates a similar approach to the work described in this thesis. The utility of this warhead system does not include the ability to defeat heavily armoured vehicles such as MBT; it does however appear to have the ability to defeat structural and SSV targets. The inclusion of a shaped charge liner in the rear warhead would improve performance of the warhead system against medium and heavily armoured targets such as MBT. The fuzing of the warhead system is controlled by the percussion fuze on the nose of the warhead system (marked 8), which restricts optimisation of the precursor warhead effect[13]. During the period when this patent was submitted, the cold war was still being fought, and it is therefore obvious that these technologies were to be employed in mine systems for counter-mobility or runway destruction. As this work was completed in the late 1970's no insensitive munitions compatible materials were in existence.

This work pre-dates the work described in the thesis by approximately thirty years; demonstrating that some of the basic elements of the Multiple Effects Warhead system have been in place for many years. However the application of the MEW warhead system cannot be fully realised without adaptive fuzing and communication systems.

[13] A single inter-charge delay will not allow optimal coupling of the precursor to the target e.g. optimal precursor stand-off to structural targets is much less than that for armour targets.

1.5.5 **Non-Line of Sight – Launch System System Overview, Raytheon promotional literature.**

The NLOS-LS is a system that comprises of CLU (Container Launch Unit) which contains fifteen missiles and a computer and communication system, Figure 1.22 shows elements of the system.

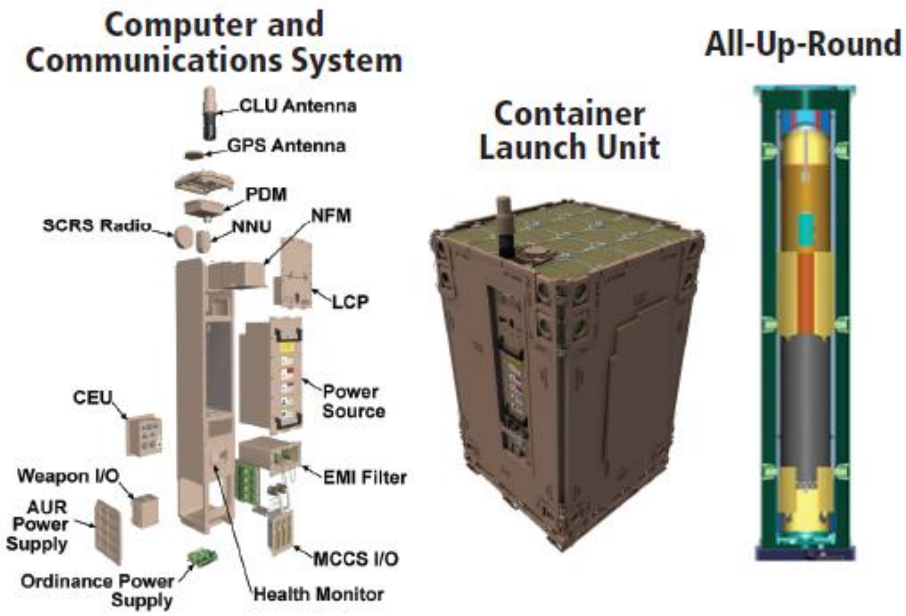

Figure 1.22: NLOS-LS elements (image courtesy of Raytheon)

This system has been adopted by the US military for use in their new Littoral Combat Ship and as part of their ground force transformation the FCS (Future Combat System). Although the FCS programme was cancelled in 2009, development of the land system under a stand-alone contract provided further funding to complete all development programmes. The system comprises of a missile that is essentially a larger variant of the Javelin ATGW, with a sectioned view of the missile shown in Figure 1.23.

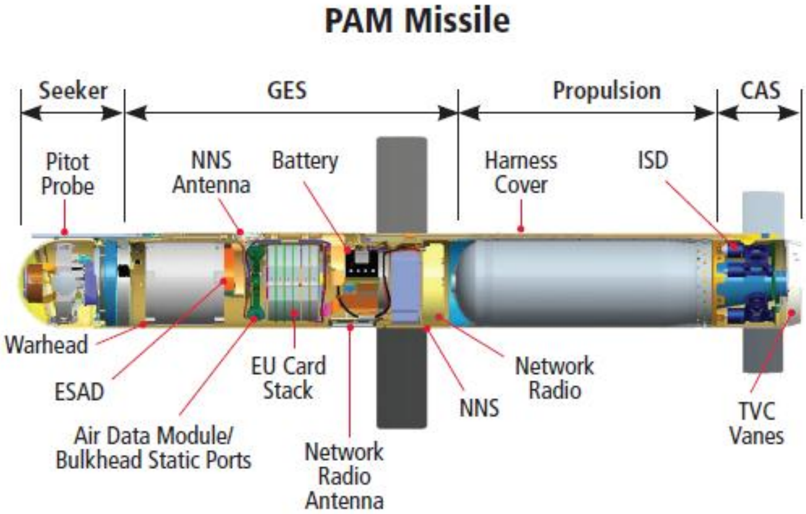

Figure 1.23: Precision Attack Munition missile system (image courtesy of Raytheon)

The PAM missile contains a single warhead; believed to be a high precision shaped charge, which is optimised for attack of heavy armour targets, and also equipped with a case that will improve fragmentation. The missile itself contains several elements which are in common with the work discussed in this thesis. The PAM missile contains a network radio compatible with the Joint Tactical Radio System. The missile is also equipped with a GPS/INS and whilst it is not known how these are integrated the presentation shows that a MEMS (Micro Electrical Mechanical System) IMU is being used. The presentation also states that both SAL and IIR are used in the seeker element to enable accurate targeting. Although not stated in the presentation (but stated in an article in Field Artillery; 1911 – 2007 The End of an Era, NLOS-LS in the AEFT (Army Evaluation Task Force); Chief Warrant Officer (Retired) Robert A Nelson and Lt Col William E Field) the forward observers will be able to communicate with the NLOS-LS system, thereby providing the capability to re-task the missile whilst in flight. The ability to communicate with the missile not only provides data on what target was attacked, but, during its flight (which may be up to 40km) it may be rerouted to attack other targets of interest.

The warhead system in this missile will only provide limited capability against structural targets. The radio system which is incorporated into the missile system is capable of being networked with the future US Army radio system, the JTRS (Joint Tactical Radio System), JTRS is to be compatible with Bowman HCDR (High Capacity Data Radio), thereby providing a level of interoperability for IP based networked radios. This is an area of research that is currently being investigated by the JTRS programme office, with initial investigations taking place in 2004, and discussed by Baddeley [25]. Use of this radio system is preferable to proprietary technologies, although the cost of the radio is not known.

This technology is well funded and has been under development for over ten years. According to reports from Defense News [26] the cost of each missile was initially approximately $304,000 when the manufacturing plant achieves full rate production, with an initial cost of $466,000 during the LRIP (Low Rate Initial Production). This level of cost is exceptional, however following further work Raytheon have projected that the system may cost between $100,000 (no IR seeker or network communication system) and $150,000, Jane's Defence Weekly [27]. This thesis details technologies which aim to provide lower cost options as they are (apart from the warhead system) COTS (Commercial Off The Shelf) technologies which have already been exploited, albeit in a variety of other systems. It must be accepted that a trade-off in absolute performance would have to be made e.g. range as a function of the ability to communicate with the system whilst in flight.

1.5.6 **Joint Attack Munition Systems Overview, Army Aviation Association of America 2009 Annual Convention, Col Michael Cavalier**

Colonel Michael Cavalier presented an overview of the Joint Attack Munitions Systems programmes, the Hellfire systems that are currently in service were described, the slide used to aid this description is shown in Figure 1.24. The systems described use well known technologies such as shaped charge, enhanced blast and fragmentation warheads.

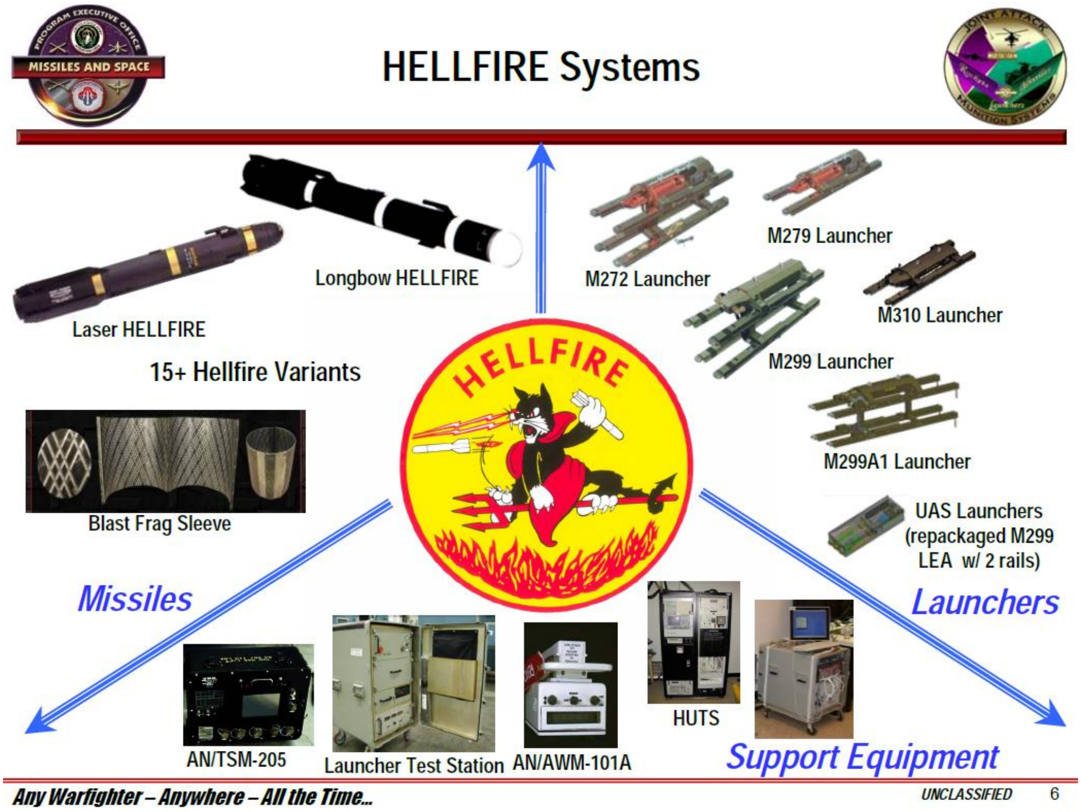

Figure 1.24: Hellfire variants (image courtesy PEO Missiles and Space)

The Hellfire systems have been in service since the Vietnam War, during which time several changes and incremental upgrades have been made. The JAGM system will integrate several of these changes.

Colonel Cavalier went on to describe the Hellfire II R missile, previously known as JAGM, Figure 1.25.

Figure 1.25: Hellfire II R Missile – outline data (image courtesy PEO Missiles and Space)

The presentation shows a tandem warhead system, with the main warhead described as having an integrated blast and fragmentation capability. From the image shown in the presentation (slide seven) it appears that the blast shield is incorporated into the main warhead, improving the ability of the main warhead to enter structural targets, similar to the approach taken in this thesis. This is a large scale programme, the research data for which is not in the public domain. UK knowledge of this programme has been restricted to the Ministry of Defence, therefore no prior knowledge of the technologies being investigated was held by the author of this thesis. The precise technologies which have been integrated into JAGM are not discussed i.e. there is no cross sectional view of the main warhead, although it is expected that this will be a high performance shaped charge inside an FTB body.

The US DoD have been pursuing a common missile approach since the mid 1990's, with the objective of reducing costs through technology reuse and modularity. This approach has also been pursued by MoD, leading to the research work discussed in this thesis, it is clear that the approach taken on JAGM is similar to this work. However the approach taken with JAGM on the warhead system is subtly different, the precursor warhead is traditional in design. When attacking structural targets the precursor will only make a narrow hole in the target, the FTB/MC will therefore have to be very robust to enable penetration of structural targets. It is known that the US DoD do not consider sandbag fortification in their structural target descriptions, typically the brick built target selected by the US DoD is triple brick construction with no cavity, a construction easier to defeat than a cavity brick wall that is fortified with a thick sandbag reinforcing wall. There is no mention of use of communication systems within JAGM. It is assumed, but not discussed, that the US DoD would wish to make their new missile systems network nodes as part of a Network Centric Warfare approach, however. The use of insensitive materials, as part of an Insensitive Munitions strategy, is also not discussed, although it is known that the US DoD have been pursuing research on less sensitive energetic materials.

1.5.7 **Follow-Thru Grenade for Military Operations in Urban Terrain, United States Patent 5107766, Harold R Schliesske and William Moscatiello, Filed July 1991.**

This patent describes a tandem warhead system that appears to be optimised for use against structural targets. The invention is described as being able to breach walls, allowing an explosive charge to be delivered to the inside of a target structure. A cross sectional view of the warhead system is shown in Figure 1.26. The FTG (Follow Through Grenade) system comprises a large precursor warhead and a small grenade which is designed to emplace within a target.

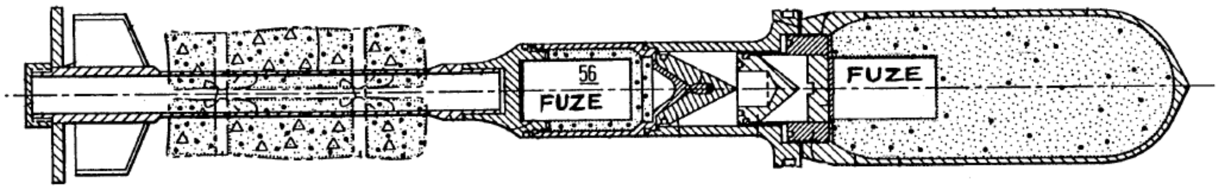

Figure 1.26: Sectioned view of FTG for MOUT system

The inventors state that the system comprises of a warhead which will penetrate target walls, with that warhead comprising of a large cased explosive charge. The system is equipped with a fuze that operates upon rapid deceleration of the warhead. This warhead appears to act in a similar manner to HESH (High Explosive Squash Head) tank ammunition. The rapid compression of the precursor warhead against the target starts to deform and spread across the target, upon this rapid momentum change the fuze operates and causes the main filling in the precursor to detonate. With the explosive spread over the target the increased blast coupling provides an effect that will cause the target to fail over a large area (this will vary depending on target toughness). The inventors also state that the 'V' shaped component to the rear of the fuze of the precursor warhead, will serve as a blast deflector, thereby reducing the blast loading on the FTG, with further protection afforded by the nose shape of the FTG which is a thick conical section. After the precursor has caused the target to fail the FTG continues the fly into the target. The fuze of the FTG is set to initiate at a preset time delay following detonation of the precursor warhead, thereby allowing the FTG to travel a sufficient distance inside the target to allow defeat of the protective capability of the structure.

The inventors do not discuss capabilities against armoured targets, it is assumed that if tests were undertaken - to characterise the technology in this patent - that claims would have been made about wider applicability of the system. It is clear that this system would have wider applicability against medium armoured systems such as the BTR series of vehicles (armour protection of approximately 8mm RHA), but with little effect being achievable against the hardest of armour targets such as MBTs. The technology discussed in this patent does share some common methods of operation, it is a tandem warhead system and it defeats structural targets by emplacing a warhead inside that target. However the mechanism providing entry into the target is completely different to that discussed in this thesis. The precursor warhead technology described in this thesis is a shaped charge, which is also applicable to anti-armour applications. The FTG, or main warhead in the system described in this patent will only provide blast and fragmentation effects, whilst sufficient to defeat personnel and lightly armoured vehicles, it is not able to defeat a heavily armoured vehicle (although some damage may be sustained). This technology is not similar to the FTB/MC warhead discussed in this thesis; the FTB/MC is capable of not only providing blast and fragmentation, but also a shaped charge jet which will penetrate the base armour of an MBT.

1.5.8 **Selectable Initiation Shaped Charges, A S Daniels, E L Baker, T H Vuong, C L Chin, B F Fuchs, S E DeFisher, US Army TACOM-ARDEC, Symposium Paper**

Daniels et al discuss work they undertook on selectable initiation of shaped charges. The relevance of this work relates to the precursor warhead which is described in this thesis. TACOM-ARDEC sought to expand the capabilities of a conventional shaped charge by increasing the number of initiation points and by placing them in positions not normally used. This work supported the FCS MRAAS (Future Combat Systems Multi-Role Armament and Ammunition System), and Common Missile where the aspiration was to achieve multiple effects with a single missile type - FCS was cancelled in 2009. The Common Missile programme transformed into the JAGM programme with a conventional design of precursor warhead. This therefore removed the exploitation path for Selectable Initiation.

Daniels et al pursued a modelling programme to understand what effects could be achieved by using various initiation points to produce diverging jets which would produce an effect over a large area, as opposed to a focussed jet, which would also be achieved by the same warhead design through initiation on the central axis of the warhead. A conical warhead design was selected, possibly to best demonstrate the desired effects. As can be seen in Figures 1.27 and 1.28, the principle of spraying the jet is related to movement of initiation points.

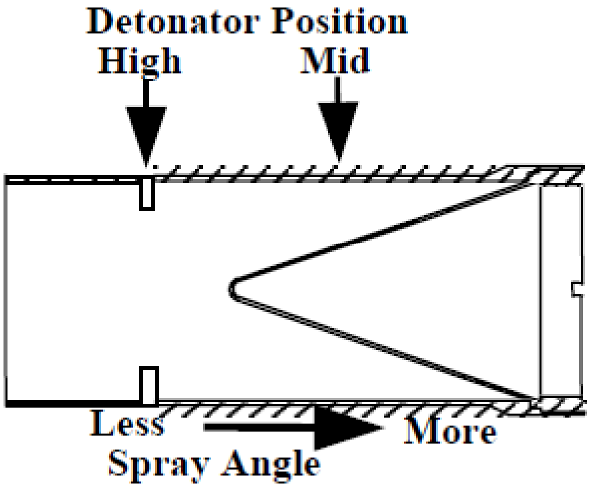

Figure 1.27: Convention for spraying shaped charge jet

The modelling study suggested that movement of two diametrically opposite initiation points from the top of the warhead, towards the bottom would result in two very different diverged (or fan) jets. The advantage offered by this type of warhead is the ability to tune the output for each target type.

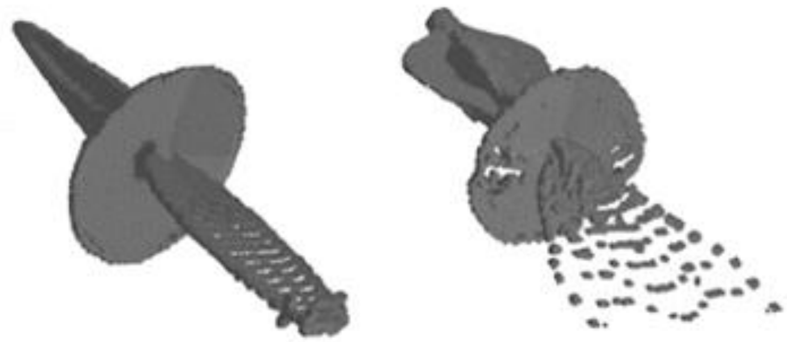

Figure 1.28: Two diametrically opposed initiation points at the top of the warhead (left) and towards the bottom of the warhead (right)

Further modelling was undertaken on variations of the initial concept and following this experimental trials were performed with a warhead which appears similar in design to that used in the Javelin and Hellfire systems. It is assumed that this design was used as it is well characterised in the simple single point initiation case. A schematic of the design is shown in Figure 1.29. As a result of using this approach a variable output was achieved, as can be seen in Figure 1.30.

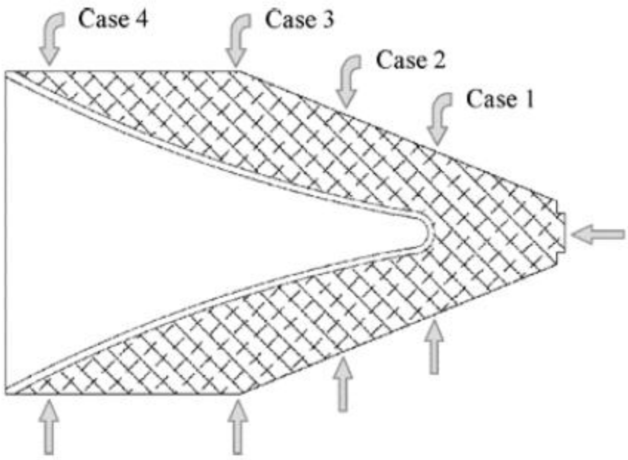

Figure 1.29: Multiple initiation points on simple shaped charge system

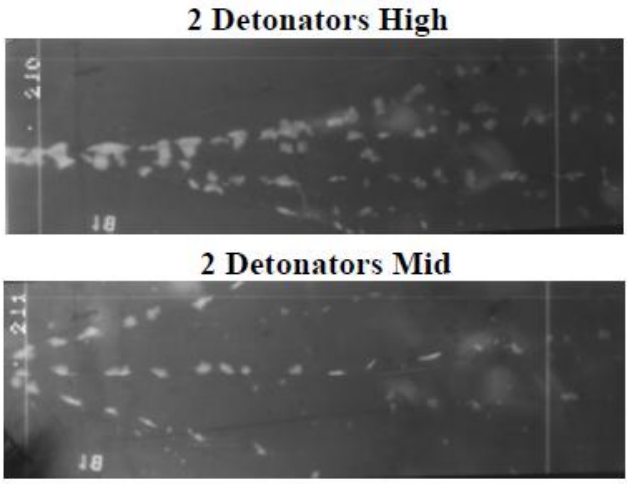

Figure 1.30: Variable output from initiation points at high and mid height points

The ability to alter the jet output does provides effects against thinner armours that would typically be used on lighter armoured vehicles such as the BTR series, as was demonstrated in a firing against a thin armour target, Figure 1.31. Also varying effects can be achieved against structural targets; the effect of a fan jet on a concrete target can be seen in Figure 1.31. It is clear that the damage sustained by the targets is significantly different than would be sustained if a straight jet were to impact the targets; this is because the jet energy has been dispersed over a wider area, thereby trading off depth of penetration for area of target damaged.

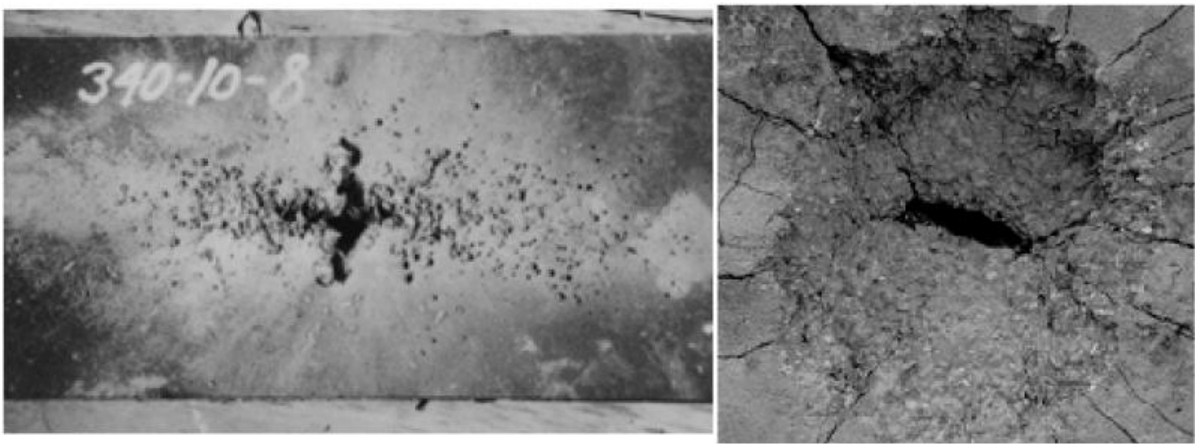

Figure 1.31: Fan jet penetration of thin armour target (left) and concrete (right)

This work demonstrates a similar approach to that taken by Fong et al (Dual Mode Warhead Technology - TACOM-ARDEC). Indeed the groups of authors come from the same US Army facility. However the approach taken by Daniels et al was to use initiation points that were in areas that would produce very unusual effects. This work was influenced by previous authors such as Brown et al of the Defence Evaluation Research Agency at Fort Halstead [28]. The work of Daniels et al demonstrated further utility, at the expense; however, of an increase in complexity in warhead construction and cost.

The work of Daniels would not have provided a suitable precursor warhead for the Multiple Effects Warhead system, since the size of precursor required to produce the requisite fan jet to defeat a thick concrete panel and provide a sufficient through hole diameter to allow the FTB/MC to enter the target, would be much larger than the

CSSJ warhead. This would therefore increase the burden on the overall system, leading to a reduction in range, and also an increase in complexity.

1.6 Motivation for Proposed Work

There are two main aims to this thesis:

- Specify a means to defeat a wide range of military targets which provides significant benefits in terms of target defeat, improvement in IM signature and logistics / integration requirements
- Specify baseline navigation, seeker and datalink technologies which exploit in-service systems that could be integrated into systems commensurate with typical ATGW systems such as Javelin and Brimstone.

1.7 Thesis Layout

This thesis can be divided into four sections. The first section, chapter 2, covers background material to set the scene and examine the previous work in areas covered by this thesis. These help clarify the novelty of the work.

The second section, chapters 3 and 4 covers the design of a MEW warhead system and the trialling of the prototype warheads. The third section, chapter 5, specifies the integration of low risk technologies to provide an advanced battlefield capability.

The final section, chapter 6 summarises the work presented in this thesis, and makes recommendations on areas of future work.

1.8 Novel Aspects of the Work

The key novel research aspects can thus be found in the following sections:

Compact Slow Stretching Jet Warhead - Section 3.4

An optimised design of precursor warhead which enables defeat of appliqué and integrated armour systems on Main Battle Tanks, whilst also enabling defeat of the fortified urban structure. This design also incorporates an insensitive main filling which reduces vulnerability to detonation following unplanned stimuli. This is an alternative approach to that taken in the design of the Anti Structures Munition which has some utility against lightly armoured vehicles.

High performance FTB/MC design – Section 3.5

Integration of a peripherally initiated high performance shaped charge into a multipurpose body. The multipurpose body incorporated an ogive to enable emplacement within structures and provides protection from precursor blast and fragmentation. This design also incorporates an insensitive main filling which reduces vulnerability to detonation following unplanned stimuli. This is an alternative approach to that taken in the design of the Hellfire AGM 114-K, M and R warhead systems which have utility against armoured vehicles, structures and personnel.

Use of JTRS SSF-G SDR – Section 5.4

JTRS is currently integrated into the PAM NLOS missile system; however its use is directly over a JTRS network. Inclusion of the Bowman waveform into the JTRS common library of waveforms has led to the ability to interoperate Bowman and JTRS.

The application of this technology within a guided weapon is an area that would form a part of future weapon development programmes.

1.9 Publications

In the course of the work for this thesis, a number of papers and presentations have been produced:

- ***An Overview of 'The integration of weapons systems into communication networks to provide an advanced battlefield capability'***

  Postgraduate Poster Presentation (Mildner lecture), UCL, March 2006
- ***Engagement of Time Sensitive Targets with Guided Ballistic Shells***

  Proceedings of the London Communications Symposium, UCL, September 2006
- ***Uninhabited Combat Vehicles on a Miniature Scale***

  Postgraduate Poster Presentation, UCL, April 2007
- ***Unexploded Ordnance, Explosive Remnants of War and Collateral Damage 'The Unzipping Warhead'***

  Postgraduate Poster Presentation (Mildner lecture), UCL, March 2008
- ***Multiple Effects Warhead for Defeat of Urban Structures and Armour***

  Proceedings of the 24th International Symposium on Ballistics September 2008, New Orleans, USA
- ***Multiple Effects Warhead Systems***

  Lecture to Defence College Guided Weapons Systems MSc course number 59, November 2008, QinetiQ Malvern, UK.
- ***Enhanced Blast***

Lecture to Defence College Guided Weapons Systems MSc course number 60, November 2009, Dstl Fort Halstead, Sevenoaks, Kent, UK.

Chapter 2

Background

This chapter will detail the general background of the warhead, guidance, communications and seeker technologies, followed by background theory of how such a MEW system would operate.

2.1 Warhead Technologies

In the simplest terms a shaped charge can be defined as a cased cylinder of explosive with a cavity at one end, which is lined with a material which can be metallic, polymeric or even glass. The geometry of the liner can vary as can its thickness. An illustration of various shaped charge designs is shown in Figure 2.1.

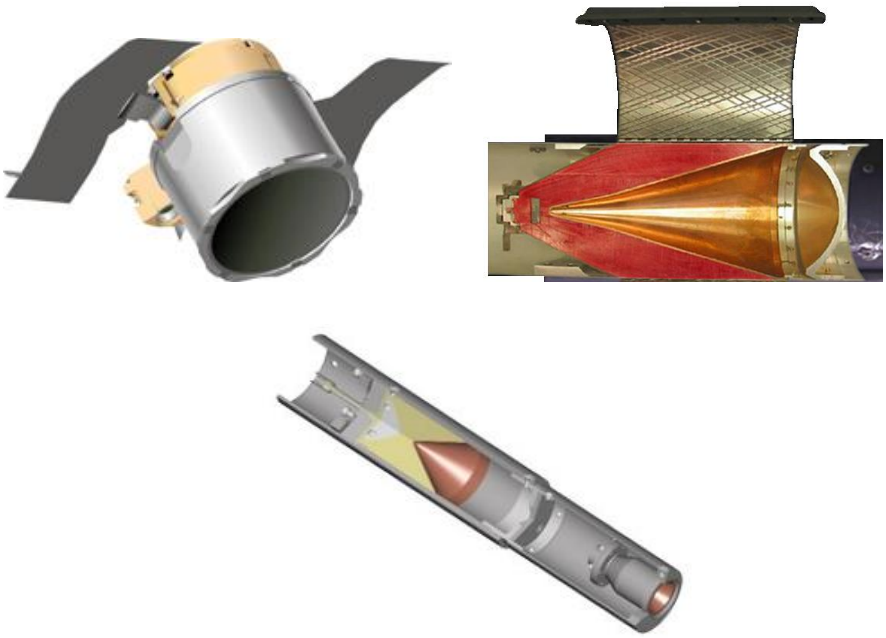

Figure 2.1: Various shaped charge warhead designs (images courtesy of Janes Information Systems and QinetiQ[14])

[14] QinetiQ image supplied by Armedforces-int.com (http://www.armedforces-int.com/article/lethal-mechanisms-warhead-technology.html)

It is widely acknowledged that the first demonstration of the hollow cavity effect for high explosives was achieved by von Foerster in 1883; however the Norwegian mining engineer Franz von Baader is alleged to have noted the focussing effects of hollow cavities in black powder charges in the late 1790's [29]. The first shaped charge was a detonator, and was patented for application in an explosive shell by G. Bloem of Dusseldorf [30]. The detonator was filled with a small explosive charge which had a cavity at one end and was lined with a hemispherical metallic material.

Charles Munroe of the Naval Torpedo Station, Newport, RI popularized the hollow charge concept with several publications; with experiments on the unlined shaped charge in 1888. In one of his experiments Munroe detonated blocks of explosive in contact with a steel plate [31]. The explosive billet was produced with the initials USN (United States Navy) inscribed on the end opposite the initiation point. The initials were reproduced on the steel plate, as shown in Figure 2.2, and the process is known as explosive engraving, this phenomenon had already been well reported by von Foerster.

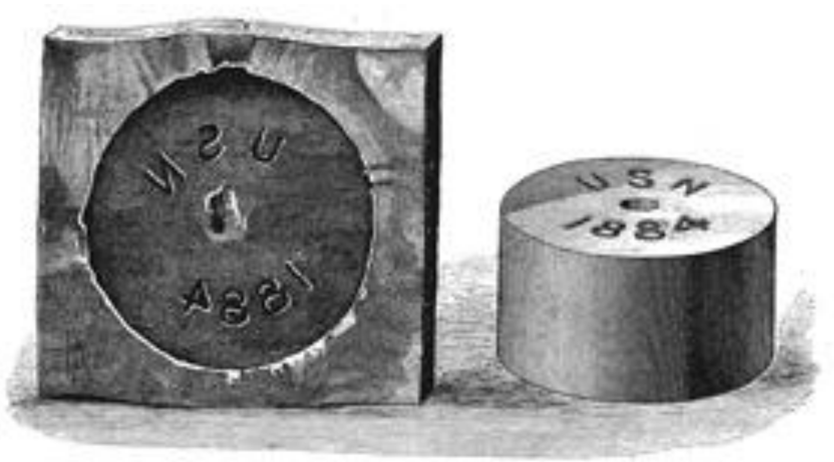

Figure 2.2: USN embossed on steel block (left) billet of 'gun cotton' explosive (right)[15]

[15] Image courtesy of Americanheritage.com

Munroe further observed that when a cavity was formed in a cylinder of explosive, opposite to the point of initiation, the depth of the crater produced in the steel target increased, leading to the observation that a deeper cavity could be formed in a steel plate using a smaller amount of explosive, Figure 2.3. He also observed that if the hollow cavity were lined with a material such as a metallic element, that the cavity would increase in depth further, as illustrated in Figures 2.3 and 2.4.

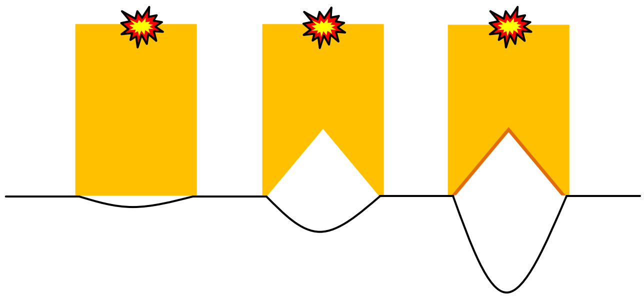

Figure 2.3: Penetration increases due to lining of hollow charge

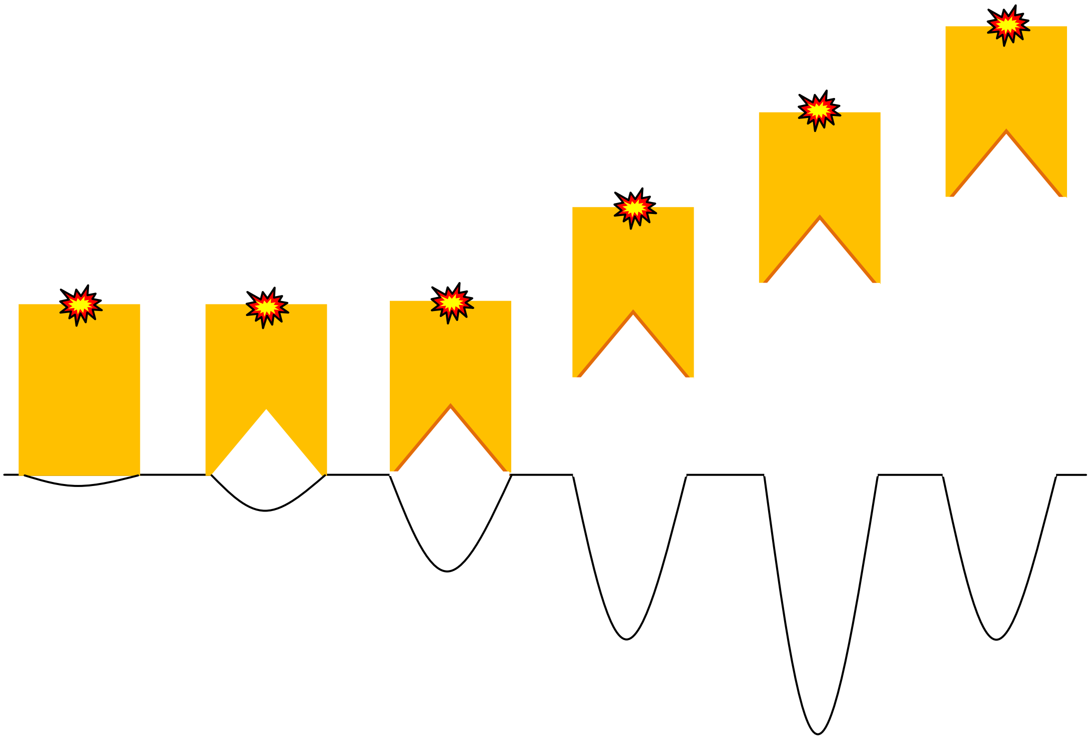

Figure 2.4: Effects of hollow charge lining and stand-off

The increase in penetration resulted from the focusing of the detonation products by the hollow cavity. The increase in penetration could be improved even further by moving the charge further away from the target material. This seems counter intuitive; however when the main explosive fill is detonated the detonation wave[16] passes through the fill and impacts the liner. The liner will collapse rapidly under tremendous pressures between 25 GPa and 500 GPa. These pressures far exceed the yield strength of the liner material, which under these conditions behaves in a similar manner as in incompressible fluid. The collapse is illustrated in Figure 2.5.

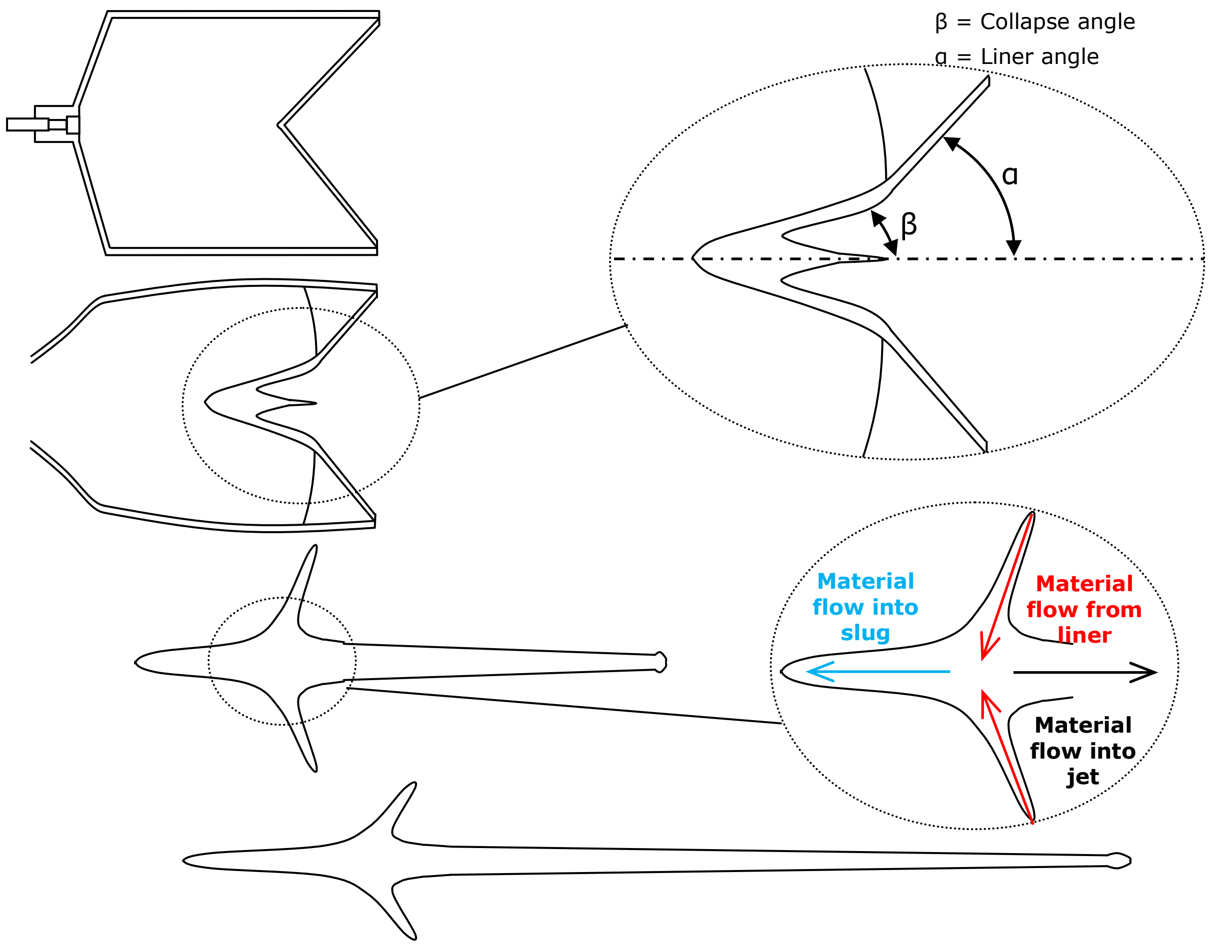

Figure 2.5: Jet formation, from liner (top) to jet (bottom)

[16] A detonation wave is a shock wave that travels at supersonic speeds through the explosive

The liner material collapses and collides on the axis of symmetry, initially material around the apex region is fed into the axis of symmetry, eventually most of the material is compressed and follows the apex material. As this happens the material is forced forwards along the axis of symmetry this process is described in more depth by Kennedy [32], Evans [33] and Blackman [34]. The liner material that is propelled forward of the stagnation zone[17] is called the Jet and the remaining material which is fed to the rear of the stagnation zone is called the Slug. This behaviour was initially described by Birkoff [35], and also verified by Clark et al. [36] [37]. In 1948 Birkoff et al. directly observed this behaviour through analysis of flash radiography, allowing him to formulate the steady state hydrodynamic jet formation theory, although the same theory was also conceived independently by Taylor [38].

As stand-off is increased, the jet length also increases; increasing the depth of target penetration. There is a limit to this phenomenon though. The last image in Figure 2.4 shows a reduction in penetration, this occurs because the ideal stand-off has been exceeded; at distances greater than the ideal stand-off the shaped charge jet will particulate as the ductility of the jet material is overcome. This allows a number of jet particles to be formed, with time the jet particles will move away from each other under the influence of independent vector properties. This movement will occur longitudinally and laterally, therefore the particles will not necessarily be aligned when they impact the target. This effect is referred to as "off-axis drift", it is an effect that occurs frequently at long stand-off and is due to the physical nature of the material used and warhead manufacture. Small inaccuracies in manufacture and assembly will cause perturbations within the jet during formation, material impurities and / or defects (even on a micron scale) can cause preferential break-up of the jet.

[17] This is a point where material that flows from the liner into the jet and slug divide.

One of the first lined shaped charges could be considered to be the device created by Munroe in 1894; it was to become known as the ‘Tin can safe opener’. This device consisted of a tin can with sticks of dynamite tied around it, with the open end of the tin can pointing downwards, as shown in Figure 2.6. The device was able to perforate the top of a steel safe where the tin can served as the liner which was projected at high velocity through the steel casing of the safe.

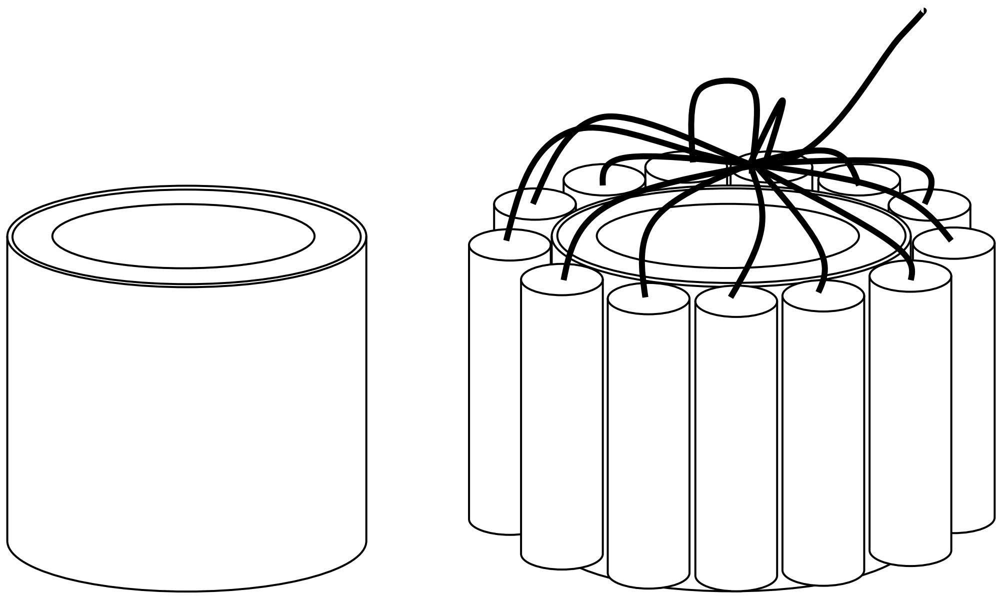

Figure 2.6: Improvised shaped charge, tin can (left) improvised device (right)

Between 1911 and 1912 patents were filed in the UK and Germany by WASAG (Westfalische Anhaltische Sprengstoff Actien Gesellschaft). The WASAG patents demonstrated the unlined and lined shaped-charge effect. Also, M. Neumann in 1911 and E. Neumann in 1914 demonstrated the unlined-cavity effect. M. Neumann shows a greater penetration into a steel plate from a cylinder of explosive with a hollow, conical cavity (247g of Trinitrotoluol) than from a solid cylinder (310g of Trinitrotoluol).

The shaped charge phenomenon is not restricted to deep liner profiles such as a 60° cone; the creation of a forward moving jet, metallic or otherwise, to produce a penetrative effect, can be achieved with varying liner profiles, leading to a number of various effects. R. W. Wood of Johns Hopkins University described what is known today as an EFP (Explosively Formed Projectile). The paper he published in 1936 [39] discussed EFPs, plastic flow of metals, deflagration and detonation. R. Eichelberger, later to become the director of the U.S. Army BRL (Ballistics Research Laboratory), credited Wood with recognizing the enhancement obtained by metal-lined shaped charges.

It was not until World War II that these early studies and experiments of the shaped charge concept produced any real exploitation opportunities. Research efforts into the lined cavity shaped-charge increased in intensity between 1935 and 1950 due primarily to World War II. The application of shaped charge development during this time is split between the British, Germans, and Americans; with all having made significant claims to the early development of modern lined cavity charges. The main discoverers of the modern shaped charge were Franz Rudolf Thomanek (Germany) and Henry Hans Mohaupt (United Kingdom/United States). Thomanek and Mohaupt independently perfected the hollow charge concept and developed the first effective lined cavity shaped-charge penetrators.

In 10 May 1940, Thomanek's hollow charges were used with resounding success at Eben Emael, Belgium. Mohaupt independently developed and introduced the shaped-charge concept to the United States. Mohaupt used shaped charges to design practical military devices ranging from rifle grenades, mortars, and 100mm diameter artillery shells. These devices were test fired at the Swiss Army Proving Ground at Thun. The British also continued to fund research to be performed to understand if the shaped-charge effect could be introduced into service munitions. Early studies concentrated on a shaped-charge rifle grenade. After a short development of approximately one year, it was introduced into British Service in November 1940 as the No.68 AT grenade. Thus, the British were equipped with the world's first hollow-charge; anti-tank rifle grenade, described in detail by Hogg in The Encyclopaedia of Infantry Weapons of World War II [40]. An image of the grenade can be seen in Figure 2.7.

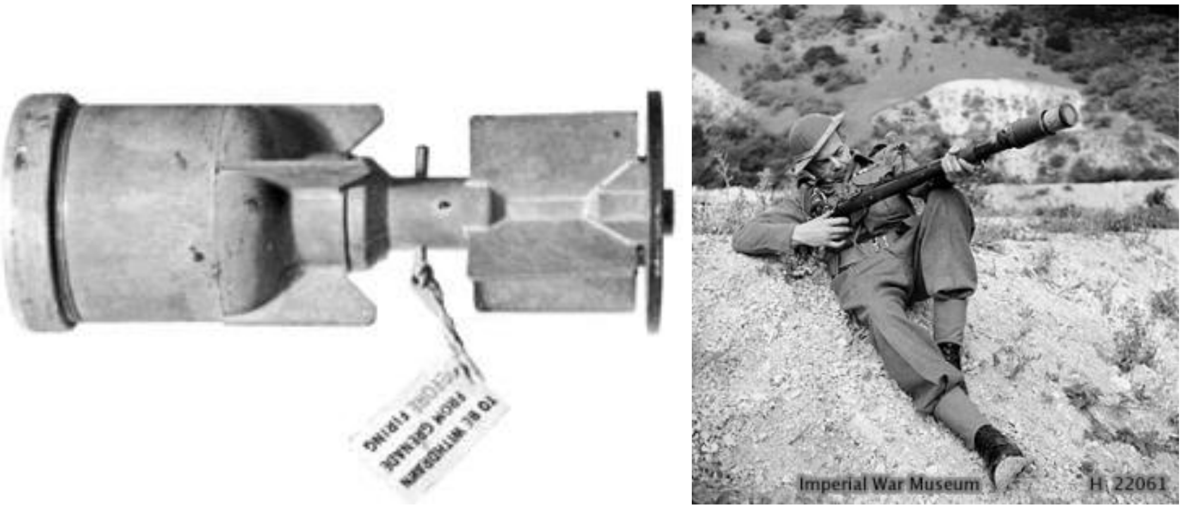

Figure 2.7: Number 68 rifle launched AT grenade and the grenade in use (images courtesy of the Imperial War Museum)

The British test results were passed on to American allies, who went on to develop the 2.36" HEAT (High Explosive Anti-Tank) machine gun grenade and the 75mm and 105-mm HEAT artillery projectiles in 1941. The machine gun grenade was modified to include a rocket motor and a shoulder launcher and became the ubiquitous Bazooka.

Shaped-charge theory continued to develop during the 1950s, boosted by the Korean War. During this time period, tremendous progress was made toward understanding the phenomena associated with shaped-charge jets. Efforts were made to improve existing shaped-charge warheads and to enhance the overall system performance. Starting in the 1950s–1960s, significant shaped-charge developments were made possible by the improvements in experimental techniques such as high-speed photography and flash radiography. Other advances have stemmed from the development of computer codes to simulate the collapse, formation, and growth of the jet from a shaped-charge liner.

Shaped charge warhead technology has been exploited extensively in guided weapons. The ability to hit an armoured target at range and destroy that target has changed the way that the military projects force. A precision strike capability can provide an enemy with a strong motive to withdraw. Guided weapons equipped with shaped charges are generally used to defeat targets that are protected with significant thickness of protective material. In the case of vehicles, armour and complex armours are used, for structural targets protection is usually afforded with significant thickness of concrete, masonry or the structure may even be buried under soil and sand. Defeating the protective elements of the target is not only related to warhead effectiveness but also to the ability of the weapon to impact the target at the correct point and to then operate in the required manner, i.e. correct operation of the fuze and time delay if one is required.

The general make-up of a fragmenting warhead is similar in nature to a shaped charge warhead; however there is no need for a lined cavity. Typically the defeat mechanism is achieved through inclusion of either a thick or dense metallic case. Upon detonation of the main explosive fill, the expanding gas (which is a product of detonation) will cause the warhead case to expand rapidly, which continues until the case fails, or fragments, at which point discreet fragments are ejected in a outward direction. This phenomenon is described in full by Mott and Linfoot in their report on fragmentation [41]. Mott and Linfoot proposed that fragmentation of a thin walled shell is the resultant of a two dimensional break-up, this can be seen expressed in Equation 2.1, where *N(m)* is the total number of fragments of mass greater than *m*, *μ* is related to the average fragment mass, and *A* is a constant. This is the simplest case that Mott and Linfoot discussed.

$$N(m) = \mathrm{Ae}^{-\frac{\mathrm{m}}{\mu}\frac{1}{2}}$$

Equation 2.1: Mott and Linfoot 2D fragmentation equation

A warhead is considered to be fragmenting if its desired effect is achieved when the munition creates fragments at, or within, close proximity to the designated target. In its pure form the explosive content of the shell is considered to only impart the kinetic energy to the fragments created. Typical examples of fragmenting munitions include grenades, mortars, shoulder-launched munitions, mines and artillery shells.

The early cannon balls of the artillery were generally stone, which tended to splinter on impact having a reasonable anti-personnel effect. However their primary requirement was that of creating a breach in the walled defences of the time. This technology became widely used when stronger barrels, and improved and more energetic gunpowder were developed, allowed the replacement of the stone ammunition by the iron cannon ball. The iron cannon ball was significantly denser than the stone previously used thus enabling defeat of fortress armour to be achieved in much shorter time periods. The iron ball however did not fragment and so the anti-personnel effect and area suppression was lost. When an anti-personnel effect was required large amounts of scrap metal, lead shot, nails etc were used in place of the ball in a manner similar to a shotgun, and known as “Grapeshot”. The name Grapeshot came from the likeness of the assembled components, which when held together as a ball would resemble a bunch of grapes. Grapeshot became a popular means of attacking advancing infantry, since the wide area effect that was achieved enabled artillery to provide a very successful defence mechanism. This fragmenting munition was used between the early 18th and early 19th centuries.

By 1788 the Master General of the Ordnance directed that the move should be made to develop an artillery piece that could accompany the cavalry. In order to fulfil this role the weapon had to be lighter in weight and as the time taken to bring the guns onto the battle field was reduced the requirement for an effective anti-personnel munition was raised.

The anti-personnel role was filled in a number of ways. One was the use against massed troops of two balls with a chain connecting them. Whilst complex to make and to control, this had devastating effects. The use of multiple fragments or projectiles had been used with older larger guns and was also now employed with the more portable weapons. One major application away from the land battle was upper deck clearing on board the tall ships of the navy of the day where there were high concentrations of men in a small area with little or no cover. In addition engagements were usually undertaken when the ships were at very short range. Loading multiple shot, however, meant a longer loading sequence than for one cannon ball as well as the additional risk to crew in having large numbers of small shot potentially rolling around the deck.

The next improvement for multiple fragments came with case (also known as canister) shot where multiple balls were contained in canisters, often cloth bags or wooden casings, which disintegrated on exiting the muzzle. The use of canister shot was the first instance of a carrier being employed to contain multiple projectiles. These served only to contain the shot during the loading process and subsequently disintegrated during firing resulting in a wide spread of small shot which had limited range, and thus limited benefit, over the extended engagement area. Such munitions could only be used against a frontal enemy and as a direct fire weapon. Due to their early and often unpredictable spread pattern they could not be used with friendly troops forward of the firing position.

The introduction of the shrapnel round was initially in the form of a cannon ball shell, previously filled with black powder, filled with multiple musket balls. It was not until the early nineteenth century that the shrapnel round became a shell recognisably similar to today's munitions. The name Shrapnel was introduced officially in 1854 as the term for the ammunition developed by Major-General Henry Shrapnel (1761-1842) an English artillery officer. The Shrapnel shell, form of cannon ball, was designed to release rather than project the payload providing a means of extending the range of delivery. An example of Shrapnel's initial design can be seen in Figure 2.8, alongside it is the improved version developed by Colonel Boxer, separated the bursting charge from the preformed fragments, resulting in more efficient distribution of fragments over the target.

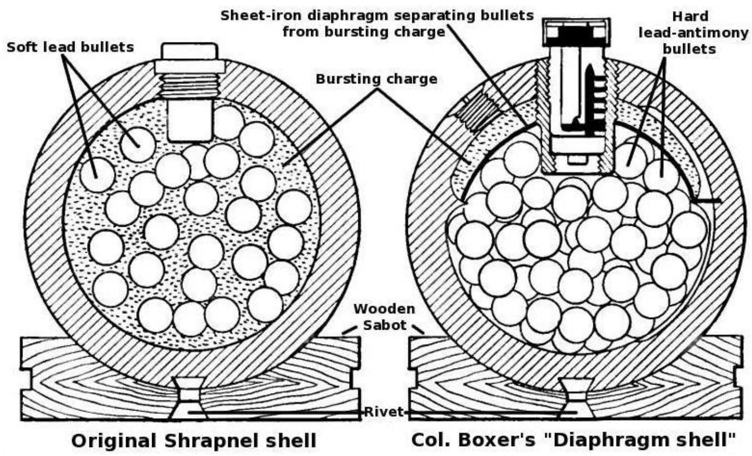

Figure 2.8: Shrapnel shell (image courtesy of Shrapnel shell manufacture, New York: Industrial Press, 1915)

By the First World War such shells could be projected up to 6000m. The term Shrapnel technically describes the lead balls of the type seen contained in the forward part of the shell, Figure 2.8, although it has since been used to describe a number of fragmenting type munitions.

The type of war fighting employed in WW1 resulted in the decline in the Shrapnel round in favour of the HE (High Explosive) round. The trenches provided cover from fragments, reducing the hit probability. The HE shell however had and still does have a naturally fragmenting body as a by-product of the requirement to deliver the high explosive within a case. The HE shell has remained the mainstay of the artillery to this day for defeating material targets with constant improvements to the fragmentation patterns of the shell casings. The HE shell has provided an effective means of generating fragments which are capable of defeating personnel and light armour targets. Figure 2.9 shows how a HE shell produces fragments from its casing, as shown by a radiograph of an experimental Ø60mm mortar warhead, performed by Rottinger et al [42].

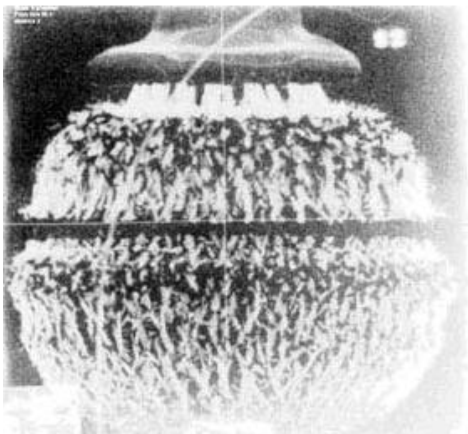

Figure 2.9: Case expansion and fragmentation

Controlled fragmentation techniques produce more predictable effects in terms of fragmentation density and ejection velocity. When using pre-formed fragments ejection velocity is much more predictable as warhead case failure is not a major factor, the casing material is much thinner as it is only used to support the explosive and the matrix of pre-formed fragments. An example of a warhead incorporating pre-formed tungsten cubic fragments is shown in Figure 2.10, as performed by Whelan when investigating early Multiple Effect Weapons warhead systems [43].

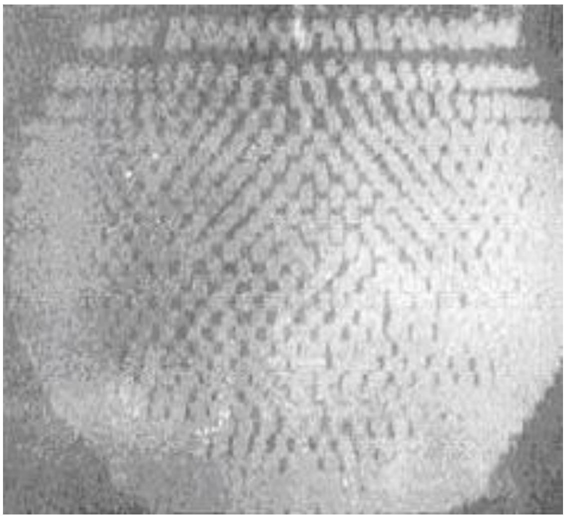

Figure 2.10: An example of pre-formed fragmentation

Preferential embrittlement using an undisclosed manufacturing technique, has been used on the AGM-114M to create weaknesses in the warhead. Internal liners have also been used to concentrate the detonation wave in the charge in a predefined pattern to preferentially fracture the warhead casing upon detonation of the main explosive fill. Another controlled fragmentation technique involves scoring or notching of the warhead case, either internally or externally. An example of an internally notched case is shown in Figure 2.11. Little work has been undertaken to understand the efficacy of internally notching over externally notching of warhead casings.

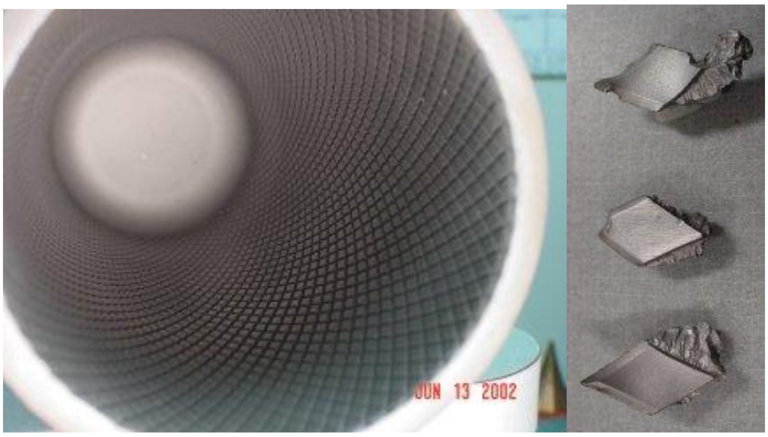

Figure 2.11: Example of the CastFrag technology (image courtesy of Miltec Machining Inc)

The notching technique is widely used as it maintains structural integrity of the warhead, and is generally cheaper than other techniques. Its principal advantage over the naturally fragmenting warhead is the ability to produce a well defined fragment density. The work performed by Rottinger et al [42] went on to compare the notched case against the naturally fragmenting case. The externally notched variant of a warhead is shown in Figure 2.12.

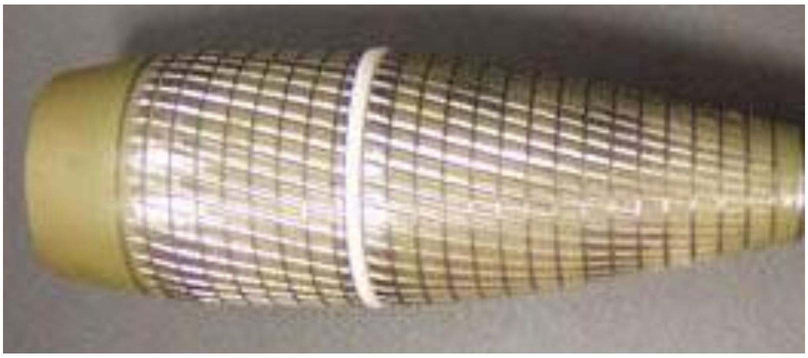

Figure 2.12: Externally notched warhead case

The aim of the experiment was to produce 0.5 gram fragments as part of an optimisation exercise to produce a fragmentation pattern that would defeat the protection worn by dismounted infantrymen. Radiography was used to observe the fragmentation pattern, in Figure 2.13, which shows that the fragment density has improved over that of the naturally fragmenting warhead case. The difference in the fragmentation pattern is clearly observable between the two techniques. The pre-notched technique provides very good results in comparison to the naturally fragmenting case, however there can be minor cost penalties in the manufacturing process.

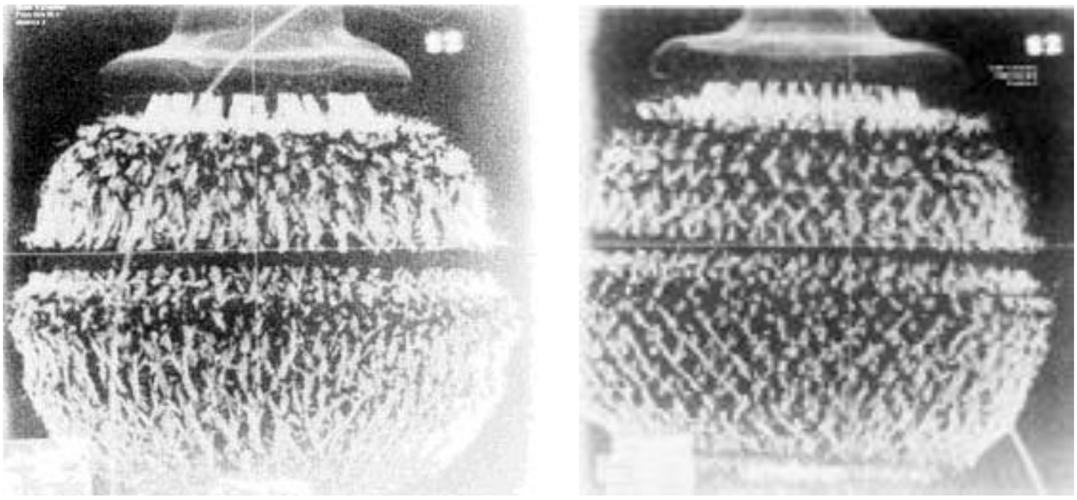

Figure 2.13: Naturally fragmenting case (left) and the pre-notched case (right)

The key mechanism that causes the fragments to be produced was characterised by Dr Richard Gurney [44]. Gurney proposed that the ratio of explosive to warhead casing was directly proportional to the ejection velocity of the fragments. The equation he derived, Equation 2.2, is a simple equation that allows the ejection velocity of a warhead casing to be calculated.

$$V = \sqrt{2E}\left(\frac{M}{C} + \frac{1}{2}\right)^{-\frac{1}{2}}$$

Equation 2.2: Gurney equation (cylindrical case)

The Gurney equation is very simple in nature, where M and C are the total masses of the warhead casing and explosive and E is the Gurney energy value relates to energy per unit mass of the particular explosive being used. This can be better visualized in the simple cylindrical case, as is shown in Figure 2.14. Fragmentation is used extensively in defeat of land air and naval targets and will continue to be used as it is has high utility and relatively low cost.

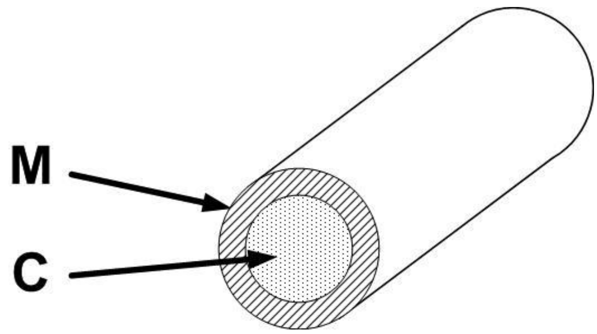

Figure 2.14: Simple 'Gurney cylinder'

Figure 2.14 illustrates a simple case where the mass (M) of case is caused to fragment by the mass of explosive (C). The ratio M/C determines the velocity of the case upon detonation of the explosive.

Another characteristic of a warhead is blast, which is the output following detonation of the explosive fill. Detonation is typically initiated by a detonator and a primary explosive initiation train or booster. The role of the detonator and booster is to create a supersonic shock wave of sufficient energy to initiate a sustained chemical reaction in the explosive. Often, detonators alone will not produce enough energy to initiate explosive charges directly, but they will however produce enough energy to initiate a booster. In turn, the booster creates enough energy to initiate the explosive.

The shock wave created by the booster compresses and raises the temperature of the explosive above the ignition point of the material, initiating a chemical reaction within a small region just behind the shock wave, known as the reaction zone. Detonation occurs when the reaction propagates through the explosive at shock velocity. The propagation of the reaction through the explosive is referred to as the detonation wave. The pressure variation as a function of distance as a detonation wave moves through the explosive, this is illustrated in Figure 2.15.

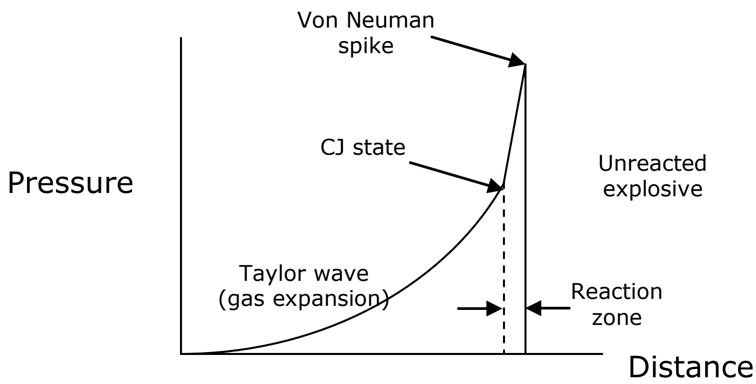

Figure 2.15: Pressure vs. Distance for a detonation wave

The rapid rise in pressure, known as the Von Neuman spike, is what brings on the reaction. The CJ (Chapman-Jouguet) point represents the state of the detonation products at the end of the reaction zone, this is discussed further by Cooper in Explosives Engineering [45]. Hot gaseous detonation products are produced from the reaction occurring in the reaction zone. These gases expand and generate a rarefaction wave that moves forward into the shock. The expansion of the detonation products is described by the Taylor wave. The shock front, reaction zone, and leading edge of the rarefaction wave are all in equilibrium, moving at a constant velocity known as the detonation velocity. The exact detonation velocity will depend upon the explosive material, as well as physical parameters such as density and degree of confinement of the explosive.

The majority of explosives are formed from the elements CHNO (Carbon, Hydrogen, Nitrogen and Oxygen). Explosives release energy through oxidation reactions. When a fuel burns with oxygen to its most stable oxidised state, the energy released is called the heat of combustion, which represents the maximum amount of energy that may be released in an explosion. However many explosives do not contain sufficient oxygen to reach full combustion, and thus the heat released during detonation, known as the heat of detonation ΔH_d^0 is less than the heat of combustion. The heat of formation ΔH_f^0 is the heat of reaction (enthalpy change) in making a particular compound from elements, where both elements and compound are at standard state conditions. The heat of detonation ΔH_d^0 is the difference between the heat of formation of the detonation products and the initial explosive, the equation allowing calculation of this is shown in Equation 2.3.

$$\Delta H_d^0 = \Sigma \Delta H_f^0 \text{ (detonation products) - } \Delta H_f^0 \text{ (explosive)}$$

Equation 2.3: Heat of detonation

The rapid expansion of the detonation products creates a shock wave in the surrounding medium, which for simplicity we will assume is ambient atmospheric air. This shock wave in air is known as a blast wave. Similar to the detonation wave discussed earlier, there is for practical purposes, a discontinuous increase in pressure, density, temperature and velocity across a blast wave. The shock-induced compression of the ambient air also leads to an increase in temperature behind the shock front. The pre and post shock states are described by conservation equations for mass, momentum and energy, collectively known as the Rankine-Hugoniot Jump equations [45] [46].

Figure 2.16 shows a typical static pressure-time curve for a blast wave. Static pressure is sometimes also referred to as side-on pressure because in order to record static pressure, the gauges are mounted side-on to the direction of travel of the blast. In Figure 2.16, t_a is the time of arrival of the blast wave, P_s is the peak pressure of the blast wave, P_a is ambient pressure and P^O is blast overpressure. The discontinuous pressure rise at the shock front is shown by the jump in pressure from P_a to P_s at time t_a. It is often convenient to express blast pressure as an overpressure, i.e. the pressure increase above the ambient level. Figure 2.16 shows an approximately exponential decrease in pressure until the pressure drops down to the (pre shock) ambient level at time $t_a + t_d$. The duration for which the pressure is greater than ambient is referred to as the positive phase, and therefore the negative phase describes the duration for which the blast pressure is below ambient. In addition to the blast pressure, another important parameter related to damage is the positive phase impulse (I), which is simply the integral of pressure during the positive phase, where *P(t)* is overpressure as a function of time. Normally, this integral is determined by calculating the area under the curve with an approximation such as the trapezoidal method, this is expressed in Equation 2.4.

$$I = \int_{a}^{a+t_d} P(t)dt$$

Equation 2.4: Positive phase impulse

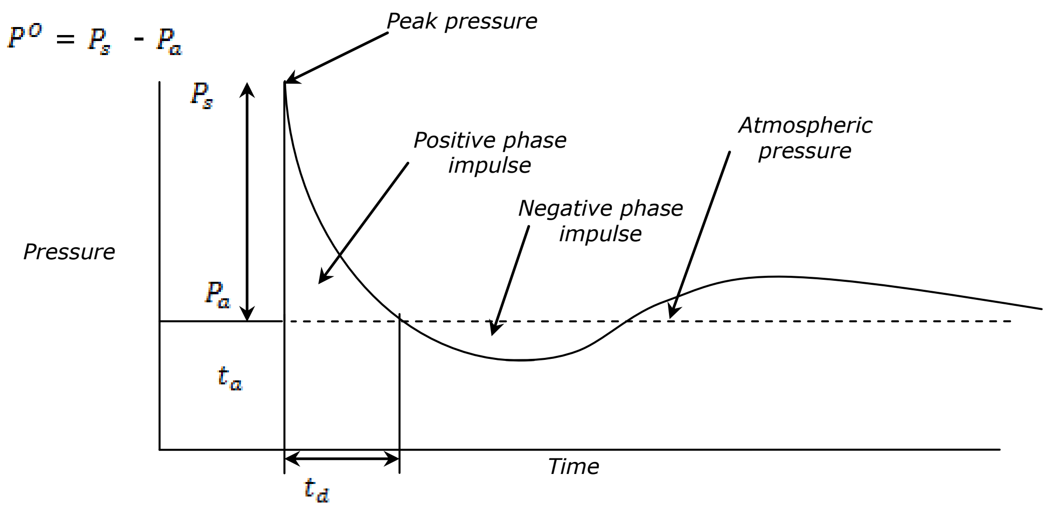

Figure 2.16: Typical pressure – time curve for a blast wave

Equivalency values are often used to relate the performance of different explosives with TNT (Trinitrotoluene) as the reference explosive. The TNT equivalent for an explosive, is the mass of TNT that would give the same blast performance as the mass of the explosive compound in question. Tables of values may be found in ConWep [47], Baker et al. [48] or Cooper [45]. Understanding the tests used to generate equivalency factors is very important. Charge geometry, munition casing, afterburning[18], and interaction with the target, all have an influence on the blast performance of a weapon. Different tests will often produce different equivalency factors for each parameter of interest. For example, ConWep gives values of 1.11 and 0.98 for determining the equivalent mass of Composition B required producing the same peak overpressure and positive phase duration, respectively as TNT. Therefore, equivalency factors are useful, but one must be aware of the limits of practical application.

[18] Afterburning occurs when the generated carbon dust and carbon monoxide (which serve as an oxidizer) mix with oxygen in such a manner that the solid carbon is first converted to carbon monoxide and then, the carbon monoxide is converted to the carbon dioxide, CO2. This creates a secondary fireball which increases blast output

Many warheads and munitions utilise a combination of blast and fragmentation to damage a target. The casing of these weapons may be naturally fragmenting or may be constructed with pre-formed fragments as previously discussed. The fragmentation process absorbs a significant portion of the explosive energy, which decreases the energy available to generate blast. This means that a cased weapon will produce a lesser blast than an uncased weapon with the same mass of high explosive. The blast of a cased weapon can be estimated using EBC (Equivalent Bare Charge), which is defined as the amount of bare explosive that would produce the same blast as the cased weapon.

An extension of blast is Enhanced Blast; this is an area of explosives technology that has only been exploited since the mid-1980's. The term 'Thermobaric' was coined by the Russian military in the 1980's and the technology and its evolution are discussed in an article written for the Foreign Military Studies Office at Fort Leavenworth [49]. The term relates to the enhancement in thermal and overpressure output from explosive compounds. The term 'Thermobaric' is derived from the Greek for temperature (Thermo) and pressure (Barikos).

The UK has procured two weapon systems which use Enhanced Blast warheads; these systems employ two different solutions to providing Enhanced Blast, the Hellfire AGM-114N and the ASM (Anti-Structures Munition). The weapons have been procured to defeat structural targets, in response to the requirement to fight in urban environments, with reduced collateral damage.

There are several variations on how Enhanced Blast functions, however a typical approach is to employ a fuel loading within the explosive filling. Such a fuel may come in the form of a metallic material; this material would be mixed with the explosive fill during the casting or filling phase. The inclusion of such additional fuel provides a key component which enables 'Secondary combustion' to be initiated. Secondary combustion occurs when the main explosive fill has detonated; as the gas cloud and flame front expands the additional fuel element is dispersed. At this point the fuel mixes with the atmosphere; the atmosphere provides sufficient oxidiser to enable the very hot fuel to burn very rapidly. This secondary combustion provides a long duration of overpressure. This overpressure, when applied inside a structure, causes structural failure of mortar joints and can lead to the collapse of wall adjacent to the blast, or even totally collapse of the structure, depending upon the NEQ (Net Explosive Quantity) of the warhead.

This technology has proliferated across the world in the last twenty years. However this technology does not offer optimal performance when used within warhead systems that employ multiple defeat mechanisms such as fragmentation and shaped charge. Enhanced Blast compositions were not considered in the research to provide a MEW system.

The three mechanisms discussed above provide a range of terminal effects. As previously stated this thesis will not discuss the all of the system components which would provide an advanced battlefield capability, since this work would cover a significant area of research which typically requires a large research team. The other key component that is required to provide an effect at the target is communication technology, which is a broad field and whose lethality[19] can be understood as contributing to accuracy and dispersion about an aim point on a target.

[19] Lethality is a combination of target acquisition, accuracy and terminal effect.

2.2 Guidance

Complex guided weapons have been in development since World War I. The United States Army Aircraft Board performed a research programme which was directed by Charles Kettering, discussed by Werrell of the Air University at Maxwell Airforce Base Alabama [50]. The programme sought to develop a long stand-off guided air delivered weapon, which would fly to the target under its own power and then attack a predetermined area, in a similar manner as the Vergeltungswaffe 1 or 'Doddlebug' in World War II. The weapon was called the Kettering Aerial Torpedo, although it was more colloquially known as the 'Kettering Bug', Figure 2.17.

Figure 2.17: The Kettering Bug being prepared for a test flight (image courtesy of US Air Force museum)

The Kettering Bug was the successor to a prototype guided weapon called the Hewitt-Sperry Automatic Airplane which flew between 1916 and 1917. The Kettering Bug was manufactured at the Dayton-Wright Airplane Company. One of the main engineers involved in development of the Kettering Bug was Orville Wright, as the chief aeronautical engineering consultant. Also involved in the programme was Elmer

Ambrose Sperry (co-inventor of the Gyroscopic compass), who designed a small Gyroscopic compass, which was used to correct the trajectory of the Kettering Bug in flight. The Kettering Bug was essentially an unmanned Biplane. Orville Wright employed much of the technology that he and his brother, Wilbur, had used to carry out their first powered flight in 1903. The Gyroscopic compass provided a mechanism to guide the Kettering Bug to its target. When it had reached the target zone the wings were detached by a cam which when moved would also shut off the small four cylinder engine. The point at which this would occur was predetermined by technicians that would calculate the total distance to the target. They would also account for errors in speed as a result of wind, which allowed the technicians to understand how many engine revolutions would be needed to achieve the required range. This number was then dialled into a simple counter which would count down to zero. When the counter reached zero the cam would then be moved to allow wing release and engine cut-off. The payload was a 180lb bomb which would explode on impact.

The Kettering Bug was only flown successfully on two occasions and although, forty five were produced none were used during World War I. The technology remained secret until World War II. The other co-inventor of the Gyroscopic Compass was Anschütz-Kaempfe, the patent for the invention being filed in the United States and Germany, allowing this technology to be available to the Germans for use in their military programmes. The Gyroscopic Compass was used extensively in World War II by the Germans to rein terror on London. It was used to provide an autopilot system which controlled the flight profile of the V-1, Vergeltungswaffe 1, retaliation weapon, the technology of which is discussed in Zaloga's book on the V-1 Flying Bomb 1942 - 52 [51]. An example of the Gyroscopic Compass can be seen in Figure 2.18.

Figure 2.18: The Kreiselkompass (Gyroscopic Compass)

A Gyroscopic Compass employs a wheel mounted on gimbals; known as a gyroscope. The gimbals allow the wheel to align itself in any direction. The wheel is spun, which allows the wheel to maintain the direction it is pointing in, in this respect the gyroscope acts in a similar manner to a magnetic compass which always points to magnetic north. When the gyroscope is initiated its axis is aligned with magnetic north, this is calibrated with a magnetic compass. The Gyroscopic Compass will remain pointing north as long as it maintains its spinning motion, this is imparted by a small motor.

The gyroscope revolutionized warfare. It allowed more accurate navigation and it also enabled guided weapons to be developed. In current military applications optical gyroscopes are widely employed. The precision of optical gyroscopes is not of the same level as the best mechanical gyroscopes, but the removal of moving parts has allowed miniaturization. Optical gyroscopes measure the phase shift between two light beams which are produced at the same time from the same source and travel through a common closed fiber-optic cable or a tightly collimated laser beam. One beam travels clock-wise whilst the other travels counter-clockwise. If the gyroscope is influenced by a rotation the light beams will reach their source point (which is now a detector) at different times. This phase shift can then be used to calculate angular velocity.

2.3 Global Positioning System

The Global Positioning System is a constellation of twenty four satellites that can provide positional data in three dimensions; GPS is controlled and operated by the United States DoD (Department of Defense). GPS allows navigation and position to be determined by measuring the distance from the user position to the precise locations of the GPS satellites as they orbit. GPS was originally developed by the DoD to meet military requirements, but was quickly adopted for civilian applications even before the system was fully operational. GPS consists of three segments.

- The space segment originally consisted of twenty four[20] NAVSTAR satellites in six orbits at an altitude of 10,900 nautical miles above the earth at an angular inclination of 50° with respect to the equator; the period for orbit is twelve hours. This configuration was adopted so that at any one time a minimum of five satellites should be in line of sight to any position on earth, as detailed in the Federal Radio Navigation Plan [52], thereby providing a high level of fidelity in positional and time data. The constellation is shown in Figure 2.19.

[20] At date of publishing the US D.o.D. had launched thirty nine satellites, of which nine were not serviceable.

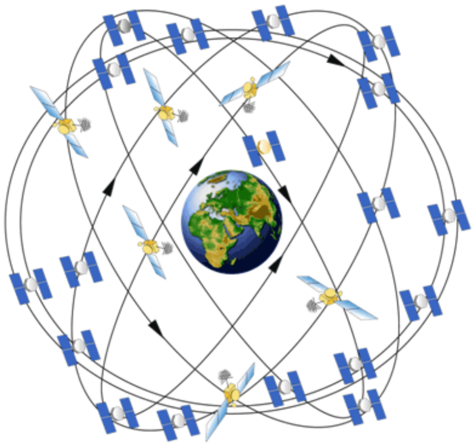

Figure 2.19: Original configuration of the NAVSTAR GPS satellites[21]

- The operational control segment is ground based and includes a master control centre which is based in Colorado Springs, Colorado, USA, with other ground stations located around the globe, Figure 2.20. The GPS operational control segment collects tracking measurements from each at monitoring station, which is equipped with a caesium atomic clock. This information is transferred to the master control centre. At the master control centre data are processed via a Kalman filter and corrections made in the ephemeris constants and biases in the onboard atomic clocks. These estimates are then used to form navigation messages, which are uploaded to the appropriate GPS satellites, which in turn transmit them to every GPS receiver in range. The navigation messages indicate where the satellites are so users can determine their position relative to them.

[21] Image courtesy of The National Executive Committee for Space Based Positioning, Navigation, and Timing (http://pnt.gov/public/images)

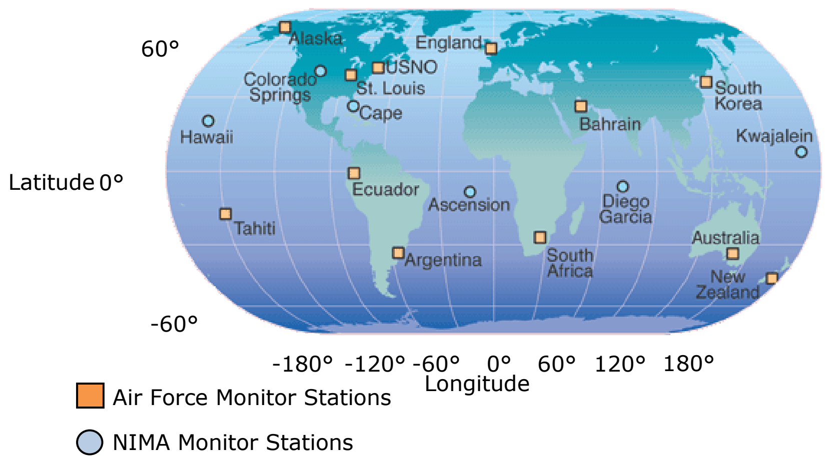

Figure 2.20: Global map of the Operational control segment

- The user segment consists of receivers specifically designed to receive, decode, and process the GPS satellite signals. Typically receivers are integrated with or embedded into other systems such as in-car navigation systems or mobile phones, although they can be stand-alone units. GPS receivers can vary significantly in design and function, depending on their application for navigation, accurate positioning, time transfer, surveying and attitude reference.

Two levels of service are offered by the GPS network service, the PPS (Precision Positioning Service) and the SPS (Standard Positioning Service). PPS is an accurate positioning velocity and timing service which is available only to authorized users; it is primarily intended for military purposes and access to the PPS is determined by the DoD. Typically access is granted to PPS if the request complies with U.S. defence requirements or international defence commitments, e.g. sales of defence equipment to foreign nations.

The PPS is specified to provide 8 metre SEP (Spherical Error Probable) (where the radius of sphere is centred at the true position, containing the position estimate in three dimensions with a probability of 50%) positioning accuracy and 10ns UTC (Universal Coordinated Time) time transfer accuracy, detailed by Kaplan and Hegarty [53]. PPS access has controlled cryptographic layers, SA (Selective Availability) and AS (Anti-Spoofing). SA is used to reduce GPS position, velocity, and time accuracy to users; pseudorandom errors are added to the satellite signals, although this function was discontinued in 2000. AS is activated on all satellites to negate potential spoofing of ranging signals, a necessary requirement as enemies of the United States wish to jam the satellite signal through ground-based transmitters or spoof military GPS receivers by transmitting a false P-code signal from another satellite. The technique encrypts the P-code (Precision code) into the Y-code (Encrypted P code), specialist equipment is required to decode the P(Y) code, P(Y) code will be superseded by M-code (Military code) which provides better protection against jamming and quicker acquisition of position as the C/A code (Coarse Acquisition code) does not have to be acquired first. The C/A code is not protected against spoofing or jamming.

The SPS is a less accurate positioning and timing service which is available to all GPS users. SPS uses the C/A code, it is available to all users worldwide and is free to use. The level of accuracy provided by this code used to be controlled by the application of SA, that resulted in a controlled service to provide 100 metre (95%) horizontal accuracy which is approximately equal to 156 metres 3D (95%). However the US DoD has deactivated the SA controls on SPS, this gives accuracy levels that are approximately the same as PPS. The SPS is primarily intended for civilian purposes, although it has potential peacetime military use. The main advantage of PPS over SPS is the tolerance to jamming and anti spoofing; this is discussed in Signals Measurements and Performance [54].

Research is currently on-going in the field of GPS modernisation. Precise Point Positioning is a new form of GPS service which can currently achieve accuracy levels of 100mm, discussed by El-Rabbany [55].

2.4 Inertial Navigation System

An INS (Inertial Navigation System) is a positioning device that, when in use, continuously measures the orthogonal linear acceleration and three angular rates of movement. INS relies on a very simple Newtonian principle; the force of a moving object $f_b(t)$ with respect to a coordinate frame can be measured through combining the linear accelerations *a(t)* of the object with the gravitational acceleration *g(t).* As the gravitational force is known the linear acceleration can be calculated through sensed force. These measurements are integrated to produce velocities in each plane, with a further integration operation of this product providing positional data. A similar operation is performed with the rate measurements to provide attitude data. Two types of INS are generally employed, strap-down and gimbaled systems.

In a gimbaled system an accelerometer triad is mounted to the inner gimbal of three gyros, and isolated from the system rotation. Its attitude remains constant in a desired orientation. These systems offer a high level of accuracy within a small range of measurement. Strap-down INS are equipped with three orthogonal accelerometers and three gyro triads fixed to the vehicle. Angular motion is continuously measured with rate sensors since the accelerometers do not remain stable (as with the gimbaled arrangement) and react to the movement of the system.

The positioning and attitude data are integrated, a process referred to as mechanization. A popular technique which is used for integration of INS and GPS is the earth fixed Cartesian mechanization. For INS / GPS integration as the INS positions after mechanization are obtained in the GPS coordinate system, this dispenses with the need to include additional coordinate transformations between the INS and GPS. This is illustrated in Figure 2.21, in a block diagram devised by Cramer [56].

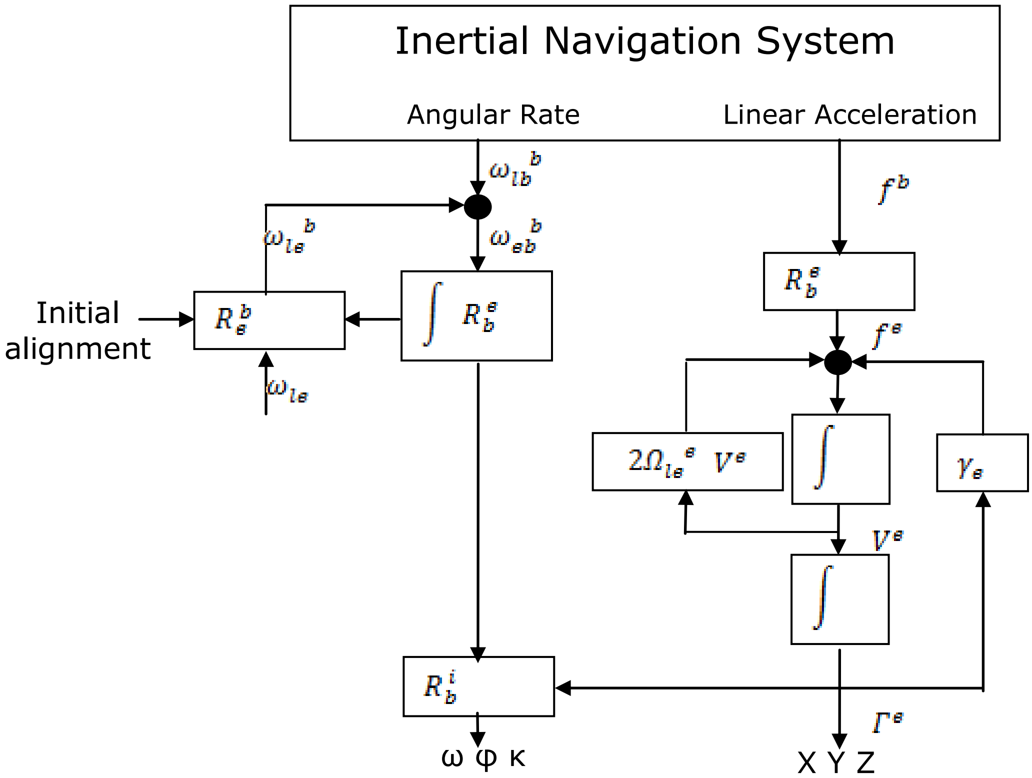

Figure 2.21: INS data mechanization algorithm[22]

Cramer states that once an initial alignment of the INS is achieved the initial transformation matrix R_e^b between the body system *b* defined by the sensor axes of the INS and the earth fixed frame *e* as the chosen coordinate frame for integration is determined. The INS angular rates (reduced by gyro drift and earth rotation ω_{ie}) matrix is updated at every measurement, R_e^b is then transposed and used to rotate the sensed linear accelerations to the *e* frame. Following corrections for the normal gravity field and Coriolis acceleration, a phenomenon that is discussed in Foundations

[22] Diagram courtesy of Cramer [56]

of Perception [57] and in the original text of Coriolis [58], integration is performed to obtain the geocentric X, Y and Z positions. Using this data in the R_e^b matrix a transformation R_b^l from the INS body frame *b* to the local coordinate frame *l* can be found. The three attitude angles (ω, φ, κ) also defined as the rotation angles for the system can be calculated from R_b^l using trigonometric functions.

2.5 GPS / INS Integration

INS and GPS may be integrated to provide a navigation system that is capable of operating with severely degraded GPS reception. This is typically not a consideration in civil applications unless the GPS antenna is often denied line of sight. However in military applications GPS may be blocked deliberately by the enemy forces in an attempt to deny essential positional data. This denial technique is currently employed by the US military to deny Taliban fighters positional intelligence [59]. Although denial of service applies to C/A code in most cases (as it is not protected against spoofing) it is possible to degrade the P(Y) code (the vulnerability of M code is not well known at this time) although this is not likely to be undertaken unless the opposing force is equipped with superior communications technology.

However unlikely the event of GPS jamming is, the integration of INS and GPS does provide an extra assurance that guidance will be provided albeit at a reduced level of accuracy. This is particularly important where operations in MOUT (Military Operations Urban Terrain) environments are being undertaken. Integration of INS and GPS data can be achieved through various means although there are two popular techniques, loose integration and tight integration.

The loose integration technique employs two Kalman filters, one for GPS measurement and one for INS measurement as described by Cramer [56]. First the raw GPS measurements are processed through a Kalman filter which is discussed in Kalmans paper on linear filtering [60] to determine the GPS position and velocity. Raw INS measurements are processed through the mechanization equation to determine the INS position and velocity. The filtered GPS data is then used as an input into the INS Kalman filter. The difference between the filtered GPS data and filtered INS data provides an estimate of the errors in position and velocity and any misalignment error. The error estimates are then used to update the position and velocity. Loose integration is a simple technique; it is robust as failure of one of the sensors will only cause a reduction in positional integrity not complete system failure. A schematic of loose integration can be seen in Figure 2.22.

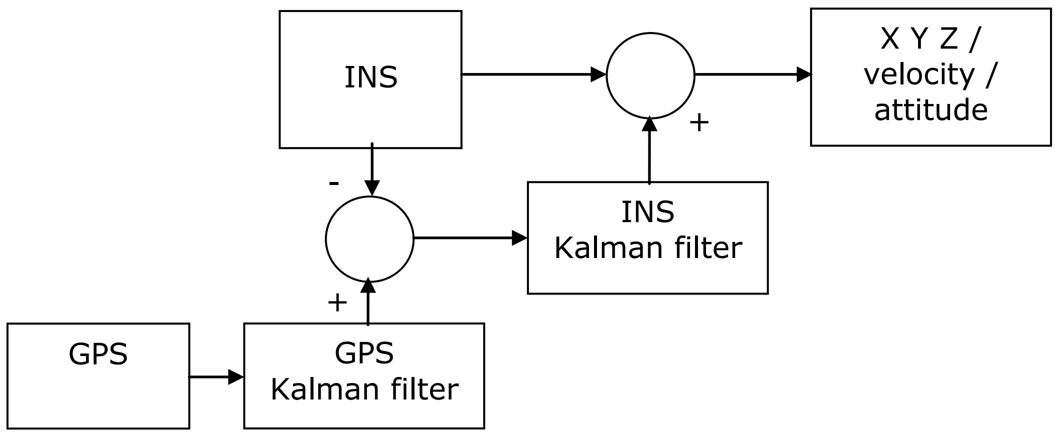

Figure 2.22: Schematic of loose integration technique

The tight integration technique uses a single Kalman filter, the INS / GPS Kalman filter. The raw INS data is processed through the mechanization equation to provide INS positional and velocity data. The raw GPS ephemeris data, combined with the INS positional and velocity data is then used to predict pseudoranges and Doppler measurement. The pseudorange and Doppler measurements are then used as inputs to the INS / GPS Kalman filter. The filter takes the difference between the pseudorange and Doppler measurements in order to provide the error estimation of position, velocity and any misalignment error. These error estimates are then used to update the position and velocity data of the INS. Tight integration can provide a very robust navigation solution even when satellite coverage is reduced to less than four satellites. The INS can still be updated due to the use of predicted and raw pseudorange and Doppler measurements [61]. Tight integration has a great deal of advantage over loose integration in urban environments. A schematic of tight integration can be seen in Figure 2.23.

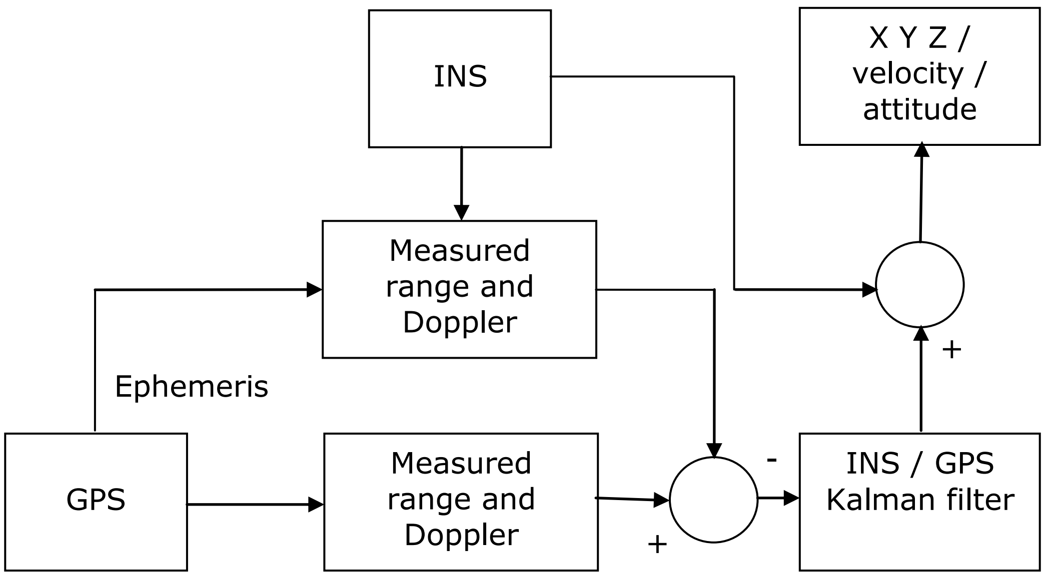

Figure 2.23: Schematic of tight integration technique

2.6 Data Links / Communication

During World War II radio usage increased significantly to serve the demands of the allied and axis forces. FM crystal-controlled radio sets made wireless communication much easier to proliferate and easier to use. With the inherently short range of VHF FM radio, radio relay was required, supported with vehicle mounted equipment. Though this required a relay station at approximately every thirty miles it massively improved flexibility of the communications network over the fixed network, which was susceptible to damage and sabotage. However a further advantage to the wireless communications network of the WWII era was the ability to integrate into the fixed line network. In tactical combat, armoured-force and artillery operators (also infantrymen using the walkie-talkie SCR-300) could talk and clearly hear over their FM sets, which remained free of the static and interference that was a common problem that the other combatants' AM radios suffered from.

Many forces now employ digital communications for voice and data employing IP (Internet Protocol). A key enabler in this field is Software Defined Radio, which is analogous to using applications on an operating system that reside on the radio hardware to enable transmission / reception on a wide range of frequencies. One of the key failing of wireless telecommunications has been the lack of interoperability. In the aftermath of 9/11, the New York Police Department and the New York Fire Departments were unable to communicate with one another; this was due to differing procurement strategies which led to different equipment purchases. Damning reports which were authored by the government and homeland defense led to increase impetus to remove this problem through 'future proofing' radio.

The US military also realised that a similar problem existed with legacy radio systems used by different armed services branches and started JTRS (Joint Tactical Radio System). JTRS has been a major force behind SDR and is responsible for the creation of the SCA (Software Communication Architecture) OE (Operating Environment) standard.

The SDR Forum, working in collaboration with the IEEE (Institute of Electrical and Electronic Engineers) P1900.1 group, has developed a definition of SDR that provides an overview of the technology and its benefits [62].

"Radio in which some or all of the physical layer functions are software defined"

As discussed in the SDR forum traditional hardware based radio devices limit cross-functionality and can only be modified through physical intervention. This results in higher production costs and minimal flexibility in supporting multiple waveform standards. By contrast, software defined radio technology provides an efficient and comparatively inexpensive solution to this problem, allowing multimode, multi-band and/or multi-functional wireless devices that can be enhanced using software upgrades. Some of the key technologies that are needed to implement software radios include:

- Wideband RF Components – These are required to allow the radio to operate over the specified operating band.
- Re-configurable processing elements – In order to allow common elements to implement any desired communications waveform or protocol, powerful re-configurable processing elements are required. Typically this would consist of microprocessors, DSP (Digital Signal Processing), and FPGA (Field Programmable Gate Arrays).
- Programmable INFOSEC – In a military context SDR must be able to maintain an INFOSEC (Information Security) capability that allows alternative encryption algorithms to be supported.

- Waveform Applications – These allow SDR platforms which are different in design to communicate with one another. The ideal SDR allows waveform applications to be downloaded to other SDR platforms.

The current deployed radio system of the British Army is Bowman, an IP based frequency hopping digital radio part of a family of radios working under CIP (Combat Infrastructure Programme). Bowman is a multi-mode radio system, making it capable of working in several operating modes, and replaced the Clansman analogue radio which had been in service with the British Army since the 1970's. Bowman is a family of digital radios, providing voice and data. However in the early 1990's it was conceived that the NEC (Network Enabled Capability) could be served by a mobile tactical internet, replacing traditional battlefield command and control mechanisms. To achieve this, the CIP BISA (Battlefield Information System Applications) project was developed. The progress of this programme is discussed at length in the National Audit Office report entitled 'Delivering digital tactical communications through the Bowman CIP programme' [63].

The ComBAT (Common Battlefield Applications Toolset) has been designed to provide the core of the battle management system, from fighting vehicles up to divisional headquarters, and an example of the ComBAT output is shown in Figure 2.24. Integrated into Bowman its role is to support command and control, as well as provide situational awareness, of military units. The purpose is to quicken the tempo of operations, and assist the survivability and effectiveness of land forces.

Figure 2.24: Example of ComBAT output (image courtesy UK Ministry of Defence)

The Digitisation Battlespace Land Infrastructure programme is designed to provide the software to enable ComBAT and other Battlefield Information Systems on Bowman to operate concurrently. It is also intended to deliver computer terminals, ancillary devices and office automation into field headquarters, enable best use of information and enable collaboration with allies, through interoperability with their systems. This is a key technology that would be used to control networked elements such as a long range guided weapon. The P-BISA (Platform Battlefield Information System Application) is to integrate ComBAT and the infrastructure software, together with existing and planned systems and sensors, into armoured fighting vehicles, such as the Challenger 2 MBT, to optimise their fighting capability.

An example of how CIP can work on the battlefield is shown in Figure 2.25. This application can also apply to the control of remote assets although the scaling of radio equipment would have to be commensurate with guided weapons.

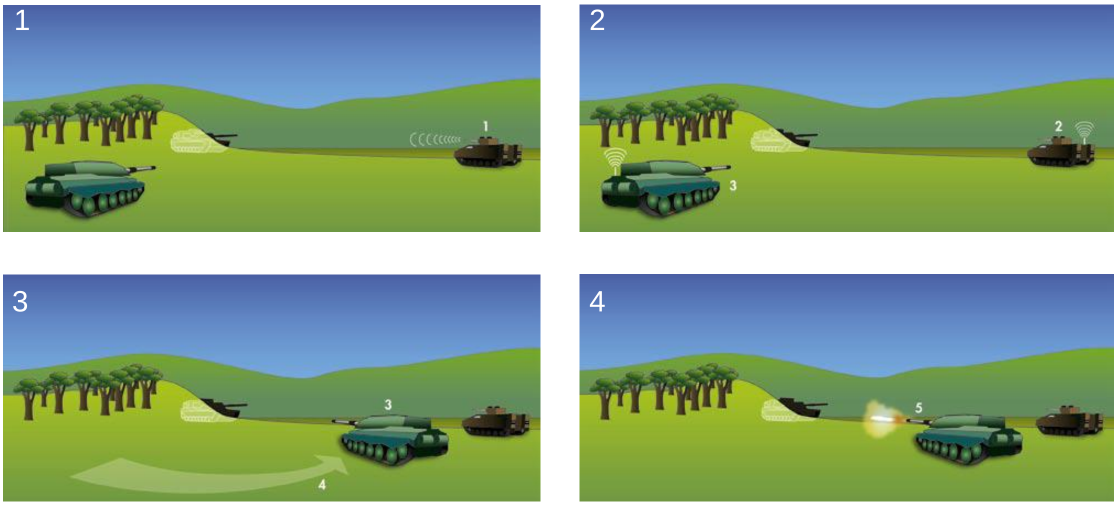

Figure 2.25: A typical battlefield use of the Bowman CIP system (image courtesy of UK Ministry of Defence)

The simplified vignette shown in Figure 2.25, demonstrates the use of CIP. In pane 1 the warrior vehicle (acting in a scout role) sights an enemy vehicle. Pane 2 shows that this imagery is then passed on to the Challenger 2. In pane 3 the Challenger 2 MBT manoeuvres into position to intercept the enemy vehicle. On reaching a position which provides line of sight to the target coordinate it fires a suitable nature of ammunition. Without this capability the tank commander in the Challenger 2 would find it difficult to provide an effective 'over-watch' function as the Scout crew would not be able to pass on their exact perspective of the situation. This is an example of shared situational awareness.

To allow CIP to function, BOWMAN uses the BOWMAN HCDR. HCDR can be considered to be an initial step towards Wideband Networking Waveform (WNWs), it encrypts data and voice with the UK government Type 1 crypto code. These radios and terminals are designed for mostly land applications in large platforms such as Challenger 2 MBT, however future applications could lead to miniaturisation allowing inclusion into larger missile systems such as Brimstone.

The use of radio communications within missile systems is not a new idea, however it has been limited to larger missile systems such as SLAM-ER (Stand-off Land Attack Missile – Expanded Response) which is equipped with an AWDL (Advanced Weapon Data Link), discussed in depth on the US Navy Website [64] and in a poster presentation by Whelan [43]. The AWDL communicates video and data to the AWW-13 Advanced Data Link pod (typically mounted on an F/A 18) enabling MITL (Man-In-The-Loop) control of the SLAM-ER missile.

However such technology is not suitable for inclusion in small missile systems due to their size and cost. Raytheon have developed a small SDR called RAFAR (Raytheon Advanced Frequency Agile Radio), it is described in the in-house Raytheon technology magazine [65]. RAFAR is small enough to be incorporated into smaller missiles because of its half duplex front end, removing the need for bulky circulators. The RAFAR radio is able to adapt in various areas, in spectrum management, rate control and transmission power adjustment. To allow this system to operate efficiently in an ad-hoc network environment novel channel access MAC (Medium Access Control) protocols are used. RAFAR is able to transmit over one of ten possible frequency channels, to receive over two channels simultaneously, adjust the transmission power on a per-packet basis, and choose from eight possible transmission rates. The novel MAC protocol was required to avoid packet collisions as a result of transmitter deafness, which is caused by the half-duplicity of the radio, whilst transmitting a packet over a given channel the radio is unable to monitor traffic over the control channel, resulting in collisions. To avoid this RAFAR uses an extension of the single channel CSMA/CA approach typically used in wireless LANs.

Other options to provide secure communication between a missile system and a controller exist. Harris, have produced a small form factor radio which will fit within the Javelin and Brimstone / Hellfire systems, shown in Figure 2.26.

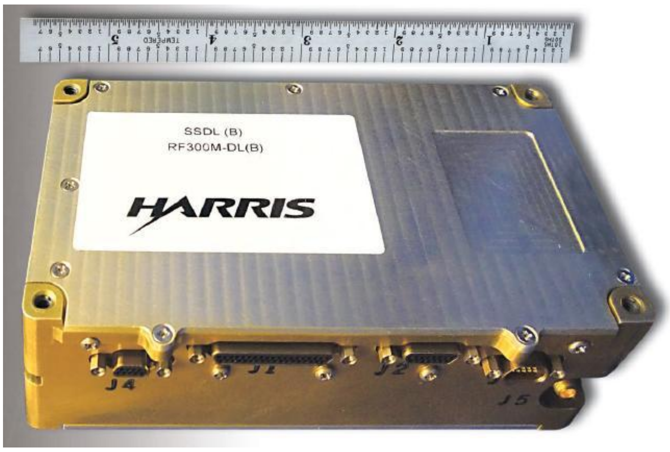

Figure 2.26: Harris Small Secure Data Link (B) (SSDL(B)) (image courtesy of Harris Inc)

The SSDL (Small Secure Data Link) is an SDR which is a single-channel lightweight, multiband, multi-mode radio developed for embedded radio applications. The SSDL is programmable via serial port and is scalable to allow multi-channel operation. The system architecture supports current and future algorithms and waveforms.

As previously discussed the US government have invested extensively in JTRS, and recently aligned to interoperate with the UK Bowman HCDR system, reported in CHIPS – the Department of the Navy Information Technology Magazine [66]. The article described demonstration of interoperability between the JTRS soldier radio and Bowman using the JBW (JTRS Bowman Waveform). The demonstration was performed in a laboratory environment, with voice and data successfully exchanged. To allow this to happen UK cryptography algorithms were deciphered. The JBW is now part of the JTRS information repository. Work on this is still on-going as detailed in a presentation given by Col Kathy Hithe at the EUCOM/AFRICOM conference [67].

2.7 Seeker Technologies

Many missile systems are equipped with sensor or seeker technology that aids identification, designation or locking on to a target. Many technologies have been used, however there are two technologies which provide a suitable combination of day/night capability and the ability to designate by a third party. These are IIR (Imaging Infra Red) and SAL (Semi-Active Laser). Other technologies exist, however IIR and SAL are very mature technologies and as such the level of reliability is high and the cost lower than other technologies such as LADAR which builds up a picture of the environment by laser scanning and then resolving each scan, or MMW sensors which use RF (Radio Frequency) to build up a map of the environment. One other issue that makes technologies such as LADAR and MMW less suitable for use in systems which would be used to engage sophisticated targets (which may be equipped with active protection systems) is the loss of stealth. LADAR and MMW (in most cases) employ active detection systems and emit signals which may be detected by laser or RF warning systems, thereby revealing their presence and possibly their position and bearing, this is illustrated in Figure 2.27. This is also a weakness of SAL however it is a weakness that can be overcome.

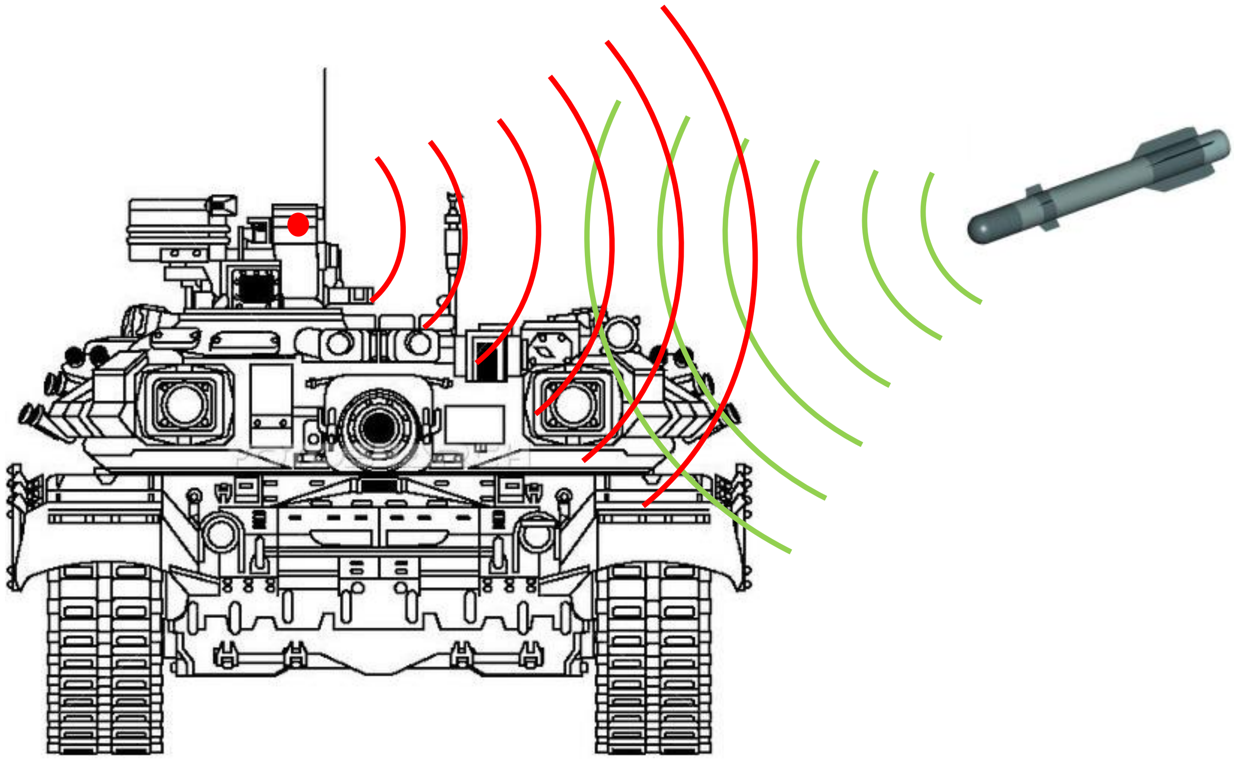

Figure 2.27: MBT equipped with a RADAR warning system[23]

As can be seen in Figure 2.27, the in-coming missile senses its target with an active system e.g. MMW. The target which is equipped with a laser and radar warner (currently radar warners are typically deployed on air platforms), detects the in-coming threat, enabling the target to deploy counter-measures which may destroy the missile.

The SAL guidance scheme relies on a laser designator, either ground-based or airborne, to illuminate the target with laser energy. The Tornado GR4 is equipped with the Litening pod III which provides enhanced target designation for weapon aiming and effectiveness. When using SAL the reflected light is sensed by the seeker on the weapon system, typically containing a quadrant photo detector. This information is then processed, within the guidance algorithm, to determine miss angles and compute the required corrections. SAL seekers provide a terminal homing capability, based

[23] Image of MBT courtesy of Steve Zaloga

upon laser energy being reflected off the target in such a geometry that the in-coming munition is able to detect it. Laser guidance has been in-service since the late 1970s typically at the 1.06μm wavelength. The term Semi-Active is derived from the passive nature of the on-board detector on the missile system, which does not emit laser energy, but collects the reflected laser energy from a laser designator, controlled by a ground or airborne source.

This technology is described in detail in the paper submitted to the Army Science Conference [68]. Typically a SAL seeker is mounted on or close to the nose of a missile system. It detects the laser reflected from the target, Figure 2.28, in a process called direct designation and is a technique typically used against targets which are not protected with sophisticated active protection systems such as ARENA, described in Jane's International Defence Review [69].

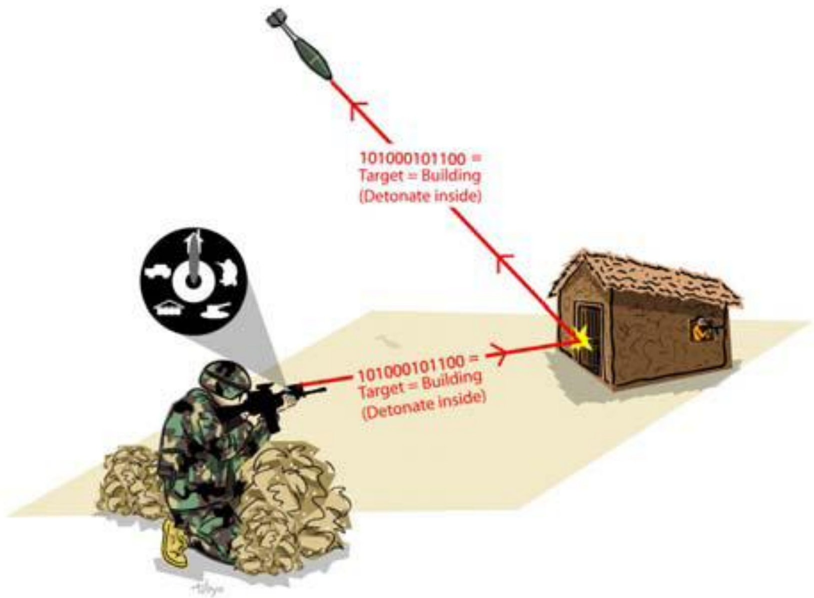

Figure 2.28: SAL designation from a third party source

Figure 2.28 shows the coding of the laser that the designator is producing. The primary purpose of encoding is to reduce "spoofing" of the laser, a simple counter measure which is employed by many technologically advanced nations. The secondary purpose of encoding is to provide instructions to the approaching system. Codes can be changed to suit the target type, the target shown in Figure 2.28 is a structural target. To yield the greatest effect against this target, penetration of the target followed by detonation of the warhead is required. The coded laser signal, therefore, not only aids designation of the target but also selection of the most suitable warhead effect.

Imaging Infrared is a technology that has been used in seeker systems for many years. The Javelin anti-armour missile system, for example, is equipped with an IIR seeker and it initially went into service with the US Army in 1996. The missile seeker assembly is encased in a hemispherical dome made of Zinc Sulphide, which is transparent to the long-wave infrared radiation of interest to the FPA (Focal Plane Array). The IR radiation passes through the dome and then through transparent lenses, made of Germanium and Zinc Sulphide that focus the energy. The IR energy is reflected specularly by mirrors of polished aluminium on to the FPA. The Javelin missile seeker is a two dimensional (2D) staring FPA of 64 x 64 detector elements. The detectors are made of an alloy of cadmium-tellurium and mercury-tellurium (Mercury Cadmium Telluride or HgCdTe), they are used in the 0.7μm – 25μm wavebands, covering the near infrared wave band through to long wave IR bands. The MCT detectors work by absorbing infrared radiation, the wavelength that is absorbed is related to the design of the detector. Absorption is achieved through excitation of an electron from the valence band into the conduction band.

The FPA processes the signals from the detectors and relays a signal to the missile's tracker. The type of picture that is generated by the CLU thermal imager can be seen in Figure 2.29; the image shown is very similar to that of the seeker.

Figure 2.29: Target image through Javelin CLU

To ensure that the seeker is able to function optimally, the FPA must be sufficiently cooled and calibrated. The CLU IR detectors are cooled using a Dewar flask[24] and a closed-cycle Stirling engine[25]. Prior to launch, the BCU (Battery Coolant Unit) activates the electrical systems in the missile and supplies cold gas from a J–T (Joule-Thompson[26]) expander to the missile detector assembly while the missile is still in the launch tube. When the missile is fired, the connection between the missile and the BCU is broken and coolant gas is supplied internally by an onboard argon gas bottle. However future Javelin variants (and other missile systems) may be equipped with uncooled IIR detectors as detailed in the paper on uncooled MCT detectors [70]

The seeker is calibrated using a "chopper" wheel, a device similar in nature to a fan. The wheel has six blades, five black blades with very low IR emissivity, and one

[24] A storage vessel which provides thermal insulation.
[25] A mechanical device which operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature levels.
[26] The Joule-Thompson effect describes the temperature change of a gas or liquid when it is forced through a valve or porous plug while kept insulated so that no heat is exchanged with the environment.

semi-reflective blade. These blades spin in front of the seeker's optics in a regular fashion, such that the FPA is continually provided with points of reference in addition to viewing the scene. These reference points allow the FPA to reduce fixed pattern noise[27].

In addition to being continuously cooled and calibrated, the platform on which the seeker rests must be stabilized with respect to the motion of the missile body and the seeker must be moved to stay aligned with the target. Javelin is designed to defeat heavily armoured MBTs and therefore attacks the target in a steep dive with the aim point being the most vulnerable area on the tank, the turret roof. To enable this the missile climbs steeply from launch to allow a steep dive down on to the target (~45°). During this flight profile the seeker must continuously stare at the target to maintain 'target lock'. This is achieved with a two-axis gimbal system, accelerometers, spinning mass gyros, and motors to drive changes in position of the platform. Information from the gyros is fed to the guidance electronics, which drive a torque motor attached to the seeker platform to keep the seeker aligned with the target.

2.8 MEW system operation

The main advantage offered by a MEW system is the ability to provide effects across a broad spectrum of objectives, with the primary objective being target defeat. The broad spectrum of targets will be discussed in Chapter 3; however an illustration of target defeat between two ends of, what could be considered to be, a broad target spectrum, is destruction of heavy armour and typical urban and rural structures. An illustration of how the two ends of the target spectrum are attacked can be seen in Figure 2.30, as can be seen two completely different approaches are required.

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[27] Noise introduced by response variations in the detector elements.

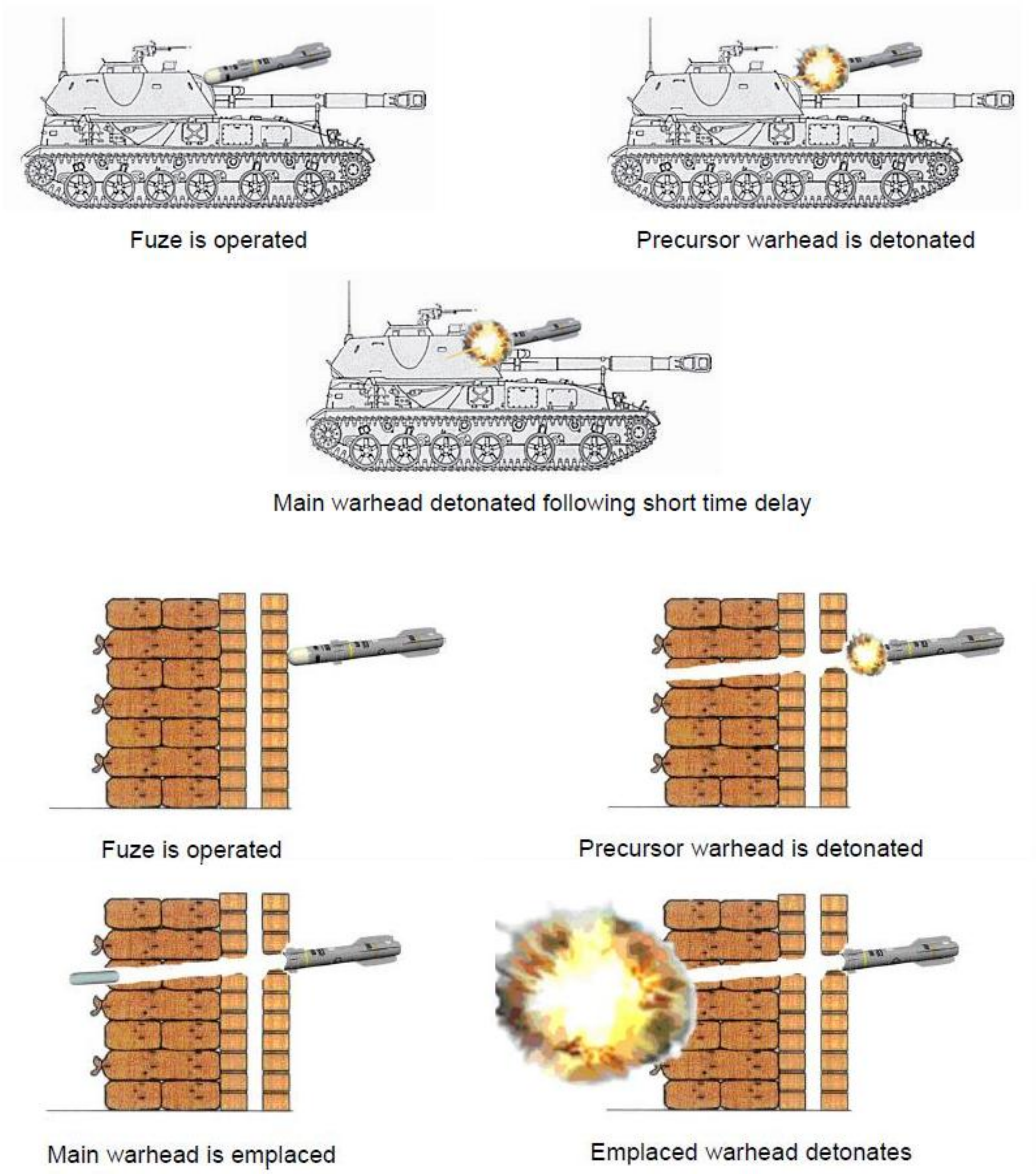

Figure 2.30: Attack of heavy armour (top) and attack of structure (bottom)

As can be seen in Figure 2.30 to defeat heavy armour targets a tandem warhead system is generally employed. The same approach is employed in the attack of structures, when a medium weight missile (such as Brimstone or Hellfire) is employed. The key difference in defeat mechanism employed is not the design of the warhead system, but the inter-charge time delay. It must be understood that there are design difference between anti-armour and anti-structures warhead systems, however, these differences can be incorporated into a single design. This 'Gestalt' approach enables one to achieve defeat of a broader spectrum of targets.

Typically attack of heavy armour targets requires a large tandem warhead system, with the main warhead (also known as the rear charge) being a 'high performance' conical lined shaped charge. Such a warhead would normally consist of a high performance explosive in the main charge, which may be encased in a high strength aluminium alloy and may be lined with Copper or another more dense material such as Molybdenum. The precursor warhead removes any appliqué armour whilst the main warhead penetrates any remaining protective base armour. When using a 50kg missile attack of structures may also require a large tandem warhead system, this is dependent on the nature of the structure being attacked. The precursor warhead should defeat the protection afforded by the structure, which may include steel reinforced concrete, sandbag reinforcement or very thick adobe clay walls. The precursor should sufficiently weaken the target to allow the main warhead to enter the structure. When the main warhead enters the target and detonates, the blast is focussed by the strength of the structure.

Essentially both forms of attack require a tandem warhead system, but the inter-charge delay for the anti-armour system is typically 500μs – 1ms, whereas the inter-charge delay for an anti-structures warhead system may be as great as 30ms. Both time delays can be incorporated into a single ESAU (Electronic Safety and Arming Unit).

2.9 Summary

This chapter detailed the technologies that are relevant to a MEW system. The basic building blocks of the warhead system are discussed along with the other subsystem aspects which include navigation, communication and seeking. The maturity of the navigation, communication and seeking subsystems has also been discussed in this chapter. Maturity of these subsystems is of importance as new technologies often present risk to integration and their architecture may not be open in nature, i.e. connectors and data sets may be proprietary.

SDR will be a crucial element in the future battlefield, it will allow transmission of voice and data. Moreover SDR will allow commanders to view all elements on the battlefield, and understand what the tasks are related to those elements, or 'nodes'. With this knowledge commanders should be better equipped to make decisions. However there is a risk of information overload, therefore some filtering techniques will be required to assist decision makers. Meta data is used as a way of withholding data from users that have no requirement to see data that does not pertain to their tasks, this approach may assist in combating the information overflow problem.

The relevance of the warhead fundamentals can be seen in the paragraph which details 'MEW System Operation'. Here the importance of the combination of shaped charge, fragmentation and blast is discussed with particular relevance to the attack of heavy armour and structures, thereby representing opposite ends of a generalised target set which usually requires the use of several weapon types. It was clear that use of a tandem warhead system would be the only appropriate approach in design of a MEW as in defeat of armour and structures there are two distinct phases, removal of the protective elements and then removal of the remaining protection.

Chapter 3

Multiple Effect Weapon Warhead System Requirements, Modelling and Design

This chapter will detail the requirements that a MEW should satisfy and the modelling and design of the MEW warhead system. A significant effort was required to predict the behaviour of the warheads singularly and as a tandem system. Firstly the requirements through to the delivery of effects will be discussed; this will specify what constraints were placed on the design of the warhead system. The warhead system design, which includes the precursor and the main warhead will be discussed along with the tools that were used to inform the design process. In this process a great deal of reliance was placed on the QinetiQ numerical modelling tool GRIM [71].

3.1 Requirements

The changing face of conflict has forced a need to engage the wider target group. This has meant that new techniques for target defeat have had to be investigated. The attack of structures, soft skinned, light and medium armoured vehicles requires different defeat mechanisms than those employed in the attack of heavy armour such as MBT. The enhancement of the current capability against the wider target group, whilst maintaining the capability against the key target of the candidate weapons system, was investigated. To enable this work to be performed several areas were investigated, including, but were not limited to, the design of MEW warhead systems and the ability to integrate such warhead systems into candidate weapons systems such as Javelin and Brimstone, Figure 3.1. Also of importance is the effect that employing such weapons as network nodes would have in both symmetric and asymmetric warfare. The target group is a key design driver, since the target size and nature must first be understood before any design work can be performed.

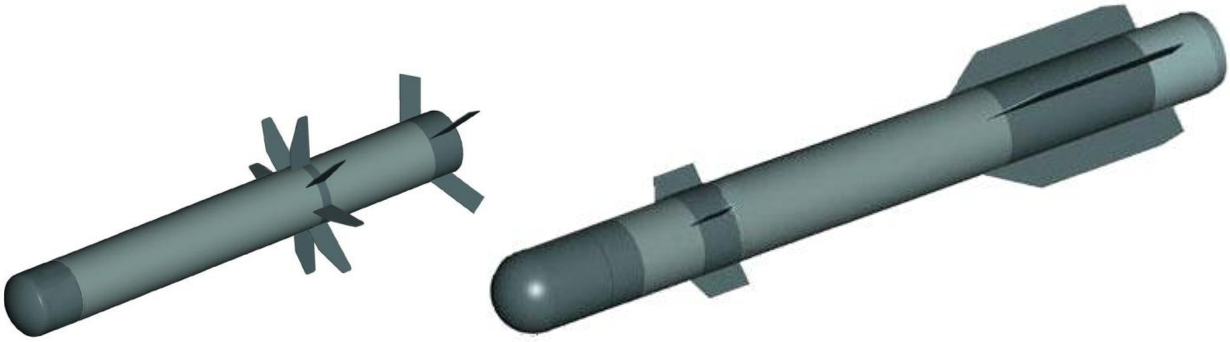

Figure 3.1: Javelin and Brimstone missile systems

The structural targets reflect target types that would be engaged by weapons in the light to medium mass bracket. Deeply buried bunkers and other such 'toughened' targets, therefore, were not considered in this work as these targets are typically attacked with large munitions such as Storm Shadow[28]. The structural targets are representative of those types of buildings that would typically be present in an urban and rural environment. The target shown in Figure 3.2 is typical on an urban structure.

Figure 3.2: Standard urban structure

[28] Storm Shadow – Air launched cruise missile type weapon

The Standard urban structure target is representative of an urban dwelling. The target shown in Figure 3.3 is a derivation of the urban structure, known as the Fortified urban structure, and is representative of an urban dwelling that has been internally fortified with a thick sandbag wall. This significantly increases the toughness of the target.

Figure 3.3: Fortified urban structure

Concrete panel targets also form part of the target group. Figure 3.4 illustrates the target developed to represent the Municipal target, which is representative of the type of wall that would be found in an office block or similar type of building.

Figure 3.4: Municipal structure

The Municipal target incorporates steel reinforcing bars at a consistent spacing below the front and rear surfaces of the target wall, however the reinforcement within the range target was altered to bring the target into line with other research programmes and in accordance with UK civil engineering practice. The strength of this target is increased significantly through the use of thicker steel reinforcing bars.

The vehicle targets reflect target types that would be engaged by weapons in the light to medium mass bracket. The vehicle targets are broken down into SSV (Soft Skinned Vehicles), light armour, medium armour and heavy armour. The targets shown in Figure 3.5 are representative of SSV targets. These targets represent light logistic vehicles, jeeps and light improvised 'troop' carriers such as a pickup truck.

Figure 3.5: Soft Skinned Vehicle targets

The targets shown in Figure 3.6 represent the light armoured vehicles. The light armoured targets comprise of vehicles such as the BTR 80, the BRDM reconnaissance vehicle and the BRDM command and control vehicle. These vehicles offer more protection than the SSV target, but the protection offered is not significant as it is designed to offer protection against fragmentation.

Figure 3.6: Light Armoured Vehicle targets

The vehicle shown in Figure 3.7 represents the medium armoured vehicle target. The vehicle is a BMP-2, which can carry troops and be armed with a Ø30mm calibre cannon and an ATGW (Anti-Tank Guided Weapon). Similar targets include the BMP-1 and BMP-3.


Figure 3.7: Medium Armoured Vehicle target (image courtesy of www.army-technology.com)

The vehicle shown in Figure 3.8 represents a heavy armoured vehicle target. The vehicle shown is a T72 M1 MBT equipped with ARENA HKDAS (Hard-Kill Defence Aids Suite). Vehicles such as this are armed with a 125mm calibre main gun, a large calibre machine gun and, in some cases, an ATGW. Similar targets include the T80 and T90 MBT.

Figure 3.8: Heavy Armoured Vehicle target (image courtesy of Jane's information Systems)

3.2 Delivery of Effect

The ability to enable defeat of two distinct target types with a single approach requires significant variance from the typical design anti-armour and anti-structures weapons. However one area of commonality remains, the requirement for a tandem warhead system. Tandem warhead systems are typically used in anti-armour and more recently in anti-structure weapons. When used at short ranges (≤1km) such a weapon must be flexible in nature, however when used at longer ranges this flexibility requires the ability to either autonomously identify a target type, armour or structure, or be able to communicate with the firer or a third party to allow the correct target to be engaged if it has not previously been identified. RoE (Rules of Engagement) provide a strict framework in the respect of target PID (Positive Identification). NATO requires that a high degree of confidence in PID is achieved prior to weapon release. The PID requirement is in place to reduce collateral damage and fratricide, as such it is important that commanders make decisions based on identification within the DRI (Detect, Recognise and Identify) parameters of the STA (Surveillance Targeting and Acquisition) assets at their disposal. Autonomous targeting is a controversial subject in this respect and will not be considered as part of this thesis. Upon identification of the target the missile must then be able to impact the target on or very close to the aim point and typically the accuracy of anti-armour missile systems is specified with the term CEP (Circular Error Probability[29]). The original concept of CEP was based on a circular bivariate normal distribution and munitions with this distribution behaviour tend to cluster around the aim point, with most reasonably close, progressively fewer and fewer further away, and very few at long distance from the aim point. For example for a CEP of 1 metre, 50% of the population will lie within 1 metre of the aim point, 43% between 1 and 2 metres, and 7 % between 2 and 3 metres. The proportion of rounds that land farther than three times the CEP from the target is less than 0.2%. When the missile impacts the target (or is in the proximity of the target if a height of burst function is more preferable) the warhead system in the weapon will have to carry out two of several possible functions, listed in Table 3.1.

Target type	Required Outcomes	
	Initial phase	Final phase
Structures	Breach external wall and internal reinforcement	Emplace within structure and detonate creating fragmentation and blast over-pressure
Soft Skinned Vehicles	Defeat external armour	Emplace within structure and detonate creating fragmentation and blast over-pressure
Light Armour Vehicles	Defeat external armour	Defeat base armour and create spall within vehicle
Medium Armour Vehicles	Defeat / disrupt appliqué armour	Defeat base armour and create spall within vehicle
Heavy Armour Vehicles	Defeat / disrupt appliqué armour	Defeat base armour and create spall within vehicle

Table 3.1: Targets and required outcomes on engagement

To defeat such a broad target spectrum with a single weapon system, several defeat mechanisms are required. The principles of Blast, Fragmentation, and Shaped

[29] Air Force Operational Test and Evaluation Center Technical Paper 6, Ver 2, July 1987

Charges have been explained in depth in the Background chapter, these effects may not necessarily be required to defeat a single target however they are required to ensure utility across the target spectrum.

Initial research into the MEW warhead system was based on previous work performed by QinetiQ in the anti-armour and anti-structures research programmes, discussed in a symposium paper written by Whelan [72] and presentation materials for the AUSA exposition [73]. It was clear that defeat of both target types required a tandem warhead system. For armoured targets the precursor warhead removes appliqué armour such as ERA. The main warhead would then perforate the base armour of the target and generate spall within the target, with the spall creating damage to internal components and ammunition which in turn may deflagrate or detonate. Defeat of structural targets does not necessarily require a tandem warhead system, although the inclusion of a precursor warhead does enable perforation of tougher urban structural targets.

3.3 Warhead System Design

In designing the warhead system previous work was drawn upon, based on the designs for high performance shaped charges such as the QinetiQ tandem shaped charge warhead system, shown in Figure 2.1, and the QinetiQ anti-structures Urban Assault Weapon. However to understand how these technologies could be applied a modelling approach was pursued. QinetiQ maintains a high performance computing facility which was used to support the modelling programme. The in-house CMD (Computational Material Dynamics) modelling code GRIM was used extensively in the modelling study. GRIM has been used to support several MoD research programmes and has been verified and validated through experimental data which has been reported at the International Symposium on Ballistics. GRIM was used to understand several aspects of the warhead designs including the penetrative ability, the impact of the use of insensitive explosive materials and the inter-charge survivability aspects.

3.4 Precursor Warhead Design

The first phase of the modelling study investigated design of the precursor warhead. A baseline design, which is shown in Figure 3.9, was used to provide a standard output to measure each precursor design against.

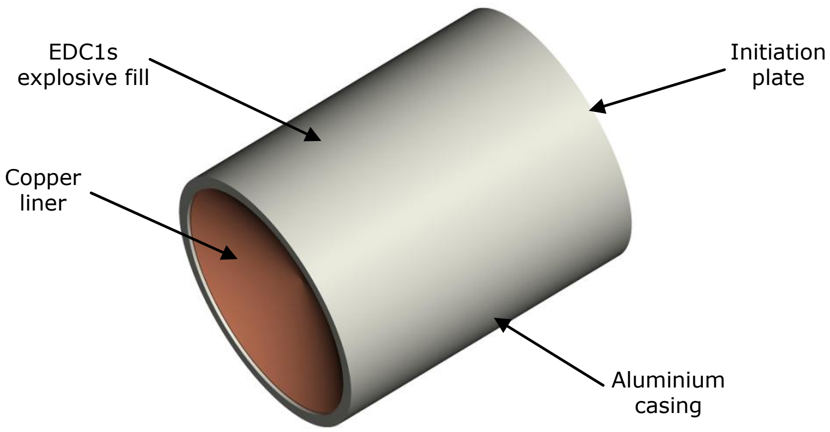

Figure 3.9: Baseline precursor – EDC1S filled

The baseline design was developed in a previous research programme and tested against a large element of the target spectrum (with range targets), the baseline warhead was filled with EDC1S (HMX 70.25%, wax 5% and RDX 24.75%) explosive, a melt-cast explosive. It was used as the main filling in the LAW 80 missile system which went out of service in the 1990's. This baseline design varied significantly from traditional precursor warhead designs seen in ATGW systems, as the typical purpose of ATGW precursor warheads is to disrupt armour systems and not to defeat the variety of targets discussed here. ATGW precursor warheads are typically designed to produce a very fast jet which is capable of penetrating several layers of passive or reactive armour systems. The design, therefore, is generally based on a conical lined shaped charge. However such a warhead will not produce the width of hole in structural targets that is required to aid emplacement of the main warhead into the structure, the defeat mechanism that is used by the Anti-Structures Munition system developed for urban warfare.

The baseline design consists of a simple cylindrical aluminium case, a high purity copper liner, a main explosive filling of EDC1S, a flat aluminium initiation plate (to the rear of the warhead) and a PIC (Precision Initiation Coupling) containing a small quantity of a PETN (Pentaerythritol Tetranitrate) based explosive, EDC8. The PIC is required to ensure that the detonation wave remains central to the longitudinal axis of the warhead, as is shown in Figure 3.10. The need to maintain a symmetric detonation wave is related to formation of the jet or projectile in the case of the precursor warhead shown in Figure 3.10.

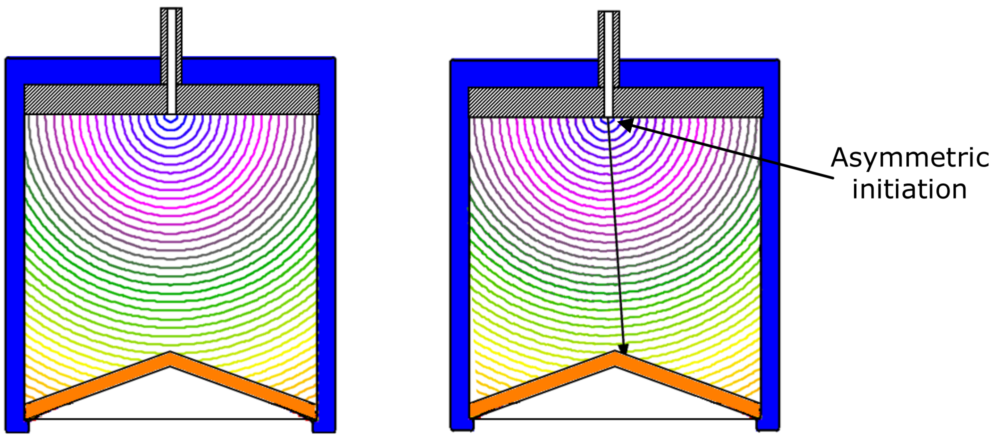

Figure 3.10: Symmetric detonation wave (left) and asymmetric detonation wave – 4° asymmetry (right)

As can be seen in Figure 3.10, if there is slight misalignment of the PIC, either through angular displacement or lateral movement from the central axis (in the case shown a movement of a few millimetres), the resulting detonation wave, following initiation, will cause the liner to deform in an asymmetric manner. Asymmetric formation greatly reduces penetration performance as some of the energy from the detonation is lost in projecting the liner laterally, and the length of jet, or projectile which is on the central axis is reduced, thereby reducing target penetration. This phenomenon was observed by Brown et al (amongst others) in experiments investigating the effects of asymmetric initiation techniques in a well understood warhead [28].

In the manufacture process the Copper liner is pressed and then heat treated (annealed) to avoid preferential break-up caused by a heterogeneous grain structure which would be present as a result of the mechanical pressing process required to create the curved liner profile. Metallographic inspection in previous research programmes, using a SEM (Scanning Electron Microscope), had shown that a pressed liner required annealing to achieve as uniform grain structure as possible. Ideally, as fine a grain structure as possible would be used in the production of the liner as a fine grain structure ($\leq 10\mu m$) aids ductility. This, however, also requires very high purity Copper (typically 99.999%), and a finely controlled mechanical working process such as flow forming, although this process is not applicable to the liner geometry being discussed here. The high ductility allows jet formation to continue to a point past that where a coarse grain structured material would start to fail, resulting in jet particulation. The liner is then finish machined on a CNC lathe, this ensures that the geometry and surface are within the required geometric and dimensional tolerances. The maintenance of a solid jet for a longer period, provides two advantages. The first is through an increase in penetration as a function of an increase in jet length, as the jet impacts the target material pressures which far exceed the yield strength are placed on the target, as a result considerations such as material strength become less important, and therefore Bernoulli [74] can provide assistance in understanding how a jet will penetrate a target, this is shown in Equation 3.1. The equation provides an approximation of penetration if a steady state is assumed where P is the total penetration; U is the target velocity (given a steady state at the penetration interface) l is jet length and V is the jet velocity.

$$P = U \frac{l}{V - U}$$

Equation 3.1: Jet penetration of target material

The second is an increase in penetration that occurs as a function of delayed jet particulation. An intact jet remains in one piece until it impacts the target material (unless jet curvature is present – this is more applicable in short stand-offs in this example) then all of the jet material will penetrate the target on a central axis. If the jet stretches out and particulates, the jet particles, Figure 3.11, will move under the influence of their own individual vectors possibly moving from the central axis, thereby reducing the depth of penetration.

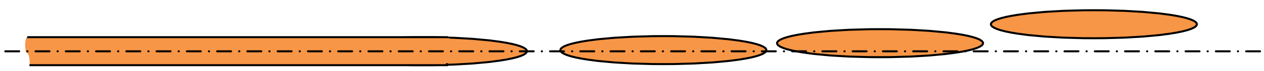

Figure 3.11: Jet particulation and off-axis movement

The precursor warhead is designed to produce a large projectile which is less sensitive to asymmetric detonation waves, and jet particulation. The liner is much thicker than that of a high performance conical shaped charge. In the case of the Baseline precursor the liner thickness is approximately double that of the normal thickness when compared to a high performance shaped charge, this results in a very thick jet. In experiments performed in the QinetiQ Fort Halstead Bomb chamber, flash radiography was used to characterise and measure jet geometry and jet velocity of the baseline warhead, Figure 3.12.

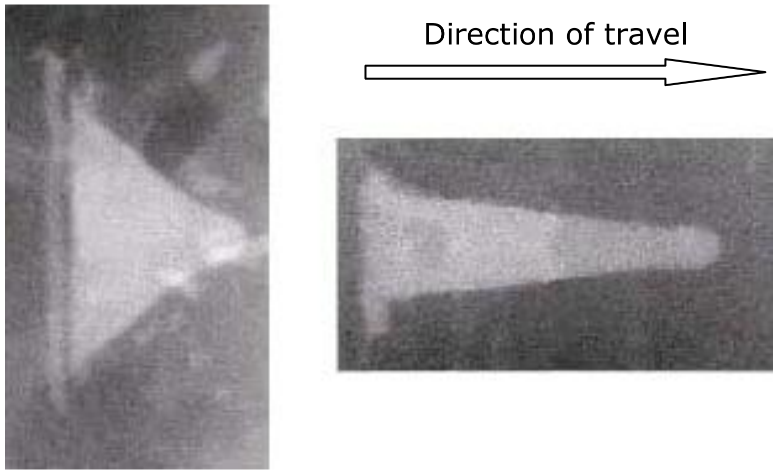

Figure 3.12: Baseline jet formation at 50μs and 85μs after detonation

It can be seen in Figure 3.12 that by 50μs the liner has inverted from its dish and then grows in length producing a rod like projectile (85μs). The shallow liner profile ensures that a very low velocity gradient is present along the length of the projectile, resulting in a projectile that does not stretch to any great extent. Typically the projectile produced by this type of warhead only stretches to a length approximately 150% of the liner diameter. Whilst this does not allow significant depth of penetration to be achieved it does result in a thick projectile which will produce a large diameter hole in the target medium. The low velocity gradient does not encourage early projectile break-up leading to off-axis particle movement, which can reduce penetration.

When the warhead research programme was initiated public domain information on Javelin and Brimstone missiles were used as guidance for systems integration. It was clear that the baseline precursor warhead would not fit within the available geometric or mass constraints. As a result a redesign of the baseline precursor warhead was required, including the adoption of an insensitive explosive filling and PIC to comply with safety guidance provided by the DOSG (Defence Ordnance Safety Group), responsible for the MoD safety policy for explosive ordnance. The GRIM 2D hydrocode[30] was used to explore two alternatives to the baseline design. The first variant was based on an evolution of the baseline warhead design; the second variant was based on a Miznay Schardin type warhead as shown in Figure 3.13.

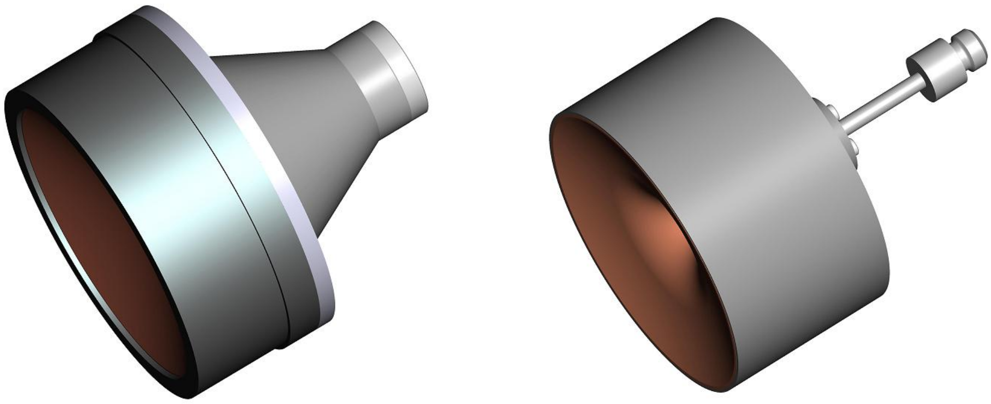

Figure 3.13: Compact Slow Stretching Jet warhead (left) the Jetting Cup Explosively Formed Projectile warhead (right)

The modelling programme investigated jet formation and target interaction. Rowanex 1001 (82% HMX and 12% HTPB) and PBXN-110 (88% HMX, 6% HTPB and 6% plasticiser) explosives were adopted as the replacements for EDC1S as the main explosive filling. Hydrocode modelling was used to observe the effects of inclusion of these PBX (Polymer Bonded Explosives) on the jet / projectile produced by the CSSJ (Compact Slow Stretching Jet), and the JC-EFP (Jetting Cup Explosively Formed

[30] A hydrocode is a computational tool for modelling behaviour of continuous media; it is typically used to model fluid flow. A hydrocode may be able to account for material condition as part of the computation. The code internal and external physical effects on a mesh which represents the item being investigated, it calculates the forces and then predicts effects

Projectile) warhead. The CSSJ warhead design was a significant variation on the baseline design. However as a significant weight reduction was required the warhead was almost completely re-designed, leaving the liner as the only remaining common component between the CSSJ and the baseline warhead. To ensure that the CSSJ precursor warhead would fit within a volume consistent with that available for the Javelin and Brimstone precursor warheads, a slight reduction in explosive head height was needed. This affected the geometry of the detonation wave, which has a smaller diameter when it starts to interact with the liner to produce an increase in projectile velocity gradient, thereby encouraging early particulation / break-up.

The CSSJ warhead design included a feature known as a boat-tail as can be seen in Figure 3.13. This section consisted of a high strength Aluminium and replaced the flat initiation plate that was incorporated into the baseline design. This had the effect of removing a significant volume of aluminium and explosive from the rear of the warhead. The removal of explosive was expected to affect jet length only slightly as it was outside of the direct line of sight of the PIC and the steel forward section of the warhead casing. It was realised that the reduction in explosive mass would lead to less combustion gases, considered a less dominant factor than that of the geometry of the detonation wave. For the initial phase of experiments each of the warheads were equipped with an EDC8 PIC, since a separate trial was required to observe the ability of an alternative initiation material to shock initiate the IM (Insensitive Munition) main explosive charge. The lower half of the warhead casing consisted of a high strength steel, a material with a yield stress of 700 MPa and tensile strength of 850 MPa.

The copper liner was exactly the same design as the baseline warhead liner, made from a high purity oxygen free copper. The material contained very little impurities making it suitable for this type of application where a homogeneous material aids production of a stable projectile that will not fracture. The liner is produced in the same manner as the baseline liner.

As stated earlier the main explosive fill was replaced with Rowanex 1001, which has a detonation pressure which is similar to PBXN-110 and is approximately 7% lower than EDC1S, this is discussed in the paper by Whelan [72]. The CSSJ design was modelled to observe any differences between it and the baseline design.

The reduction in explosive head height led to a slight decrease in detonation wave radius that would typically lead to a decrease in projectile tip velocity as the energy deposited by the explosive would occur over a (comparatively) longer period. The reduction in detonation pressure was an area of concern that led to the steel forward body section. This steel body section was required to provide an increased shock reflection over that which would occur if the aluminium casing were used. This increased confinement was thought to provide an increase in the tail velocity of the projectile and designed to recoup some of the energy lost through the alteration of the detonation wave geometry due to the reduction in the explosive head height. The confinement was also believed to increase the duration over which high pressure would be exerted by the detonation products on the forming projectile, as confirmed by work and a patent filed by Walters of the Army Research Laboratory [75] . Walters detailed the design of a precursor warhead which was heavily confined to recoup energy which had been lost, especially as up to 75% of the explosive from the base-line warhead design had been removed in an effort to provide a less violent environment for the main warhead in a tandem warhead system.

The GRIM2D hydrocode was used to model projectile formation and target interaction. The first modelling phase investigated projectile, formation for comparison with modelling data from the baseline warhead. Plots of predicted projectile shape from the first modelling phase can be seen in Figure 3.14.

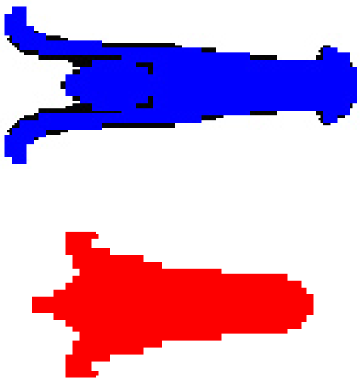

Figure 3.14: SSJ projectile at 95μs (top) and CSSJ projectile at 100μs (bottom)

The projectile formed was similar to that of the baseline with a reduction in overall length of 25%. The length of the core of the projectile, however, was 18% shorter than that of the baseline. The major difference between the two designs was the 25% reduction in tip velocity, at approximately 100μs and thought to be related to the reduction in explosive content and the slight change in detonation wave geometry. Observation of previous trials data from firings of the SSJ suggested that the SSJ warhead was greatly over matching all of the targets. A reduction in output energy, was not considered grounds for discontinuing further investigation of this design.

The CSSJ warhead was modelled to investigate its target defeat characteristics, initially penetration of RHA was modelled. The RHA target plate was representative of the thickest section of a typical FSU (Former Soviet Union) light armoured fighting vehicle. GRIM2D was again used to observe projectile / target interaction. The baseline warhead was also modelled to provide a comparator. Plots from the second modelling phase can be seen in Figure 3.15. As experimental performance data for the

SSJ existed at stand-off distance of 1CD, the simulations were therefore designed to provide a comparison at this stand-off.

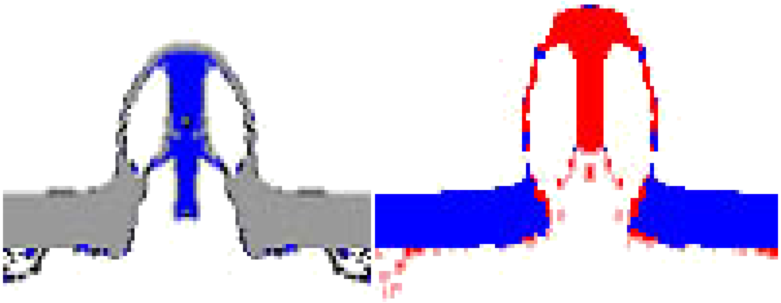

Figure 3.15: Perforation of RHA plate, SSJ (left) and CSSJ (right)

The hydrocode predictions are shown in Table 3.2, where it is evident that there was a slight difference in hole diameter produced by the SSJ and the CSSJ. However it is also evident that the target was easily overmatched.

Precursor Type	Explosive Filling	Stand-off (CD)	Hole Diameter (% of Baseline at 1CD)
Baseline	EDC1s	1	100
CSSJ	ROWANEX 1001	1	82
CSSJ	ROWANEX 1001	2	90
CSSJ	ROWANEX 1001	3	90

Table 3.2: Hydrocode plate penetration modelling results

Although 1CD is a representative stand-off for both crew served and air launched weapons, modelling was performed at other stand-offs, to observe any sensitivity in case other studies concluded that warhead detonation at longer stand-offs would be required to yield other system benefits. The hole profile in each of the simulations, from 1CD to 3CD stand-off, followed a trend of being approximately constant 80% of the baseline in diameter with some signs of shearing on the rear face, as can be seen in Figures 3.16 and 3.17. A significant 'peeling' of material from the rear surface of the target is also apparent. The material in this region is under significant pressure which may lead to it shearing away from the target plate. This shearing suggested that a great deal of target material would be projected from the rear of the target as the failure of the plate may be dominated by fracture.

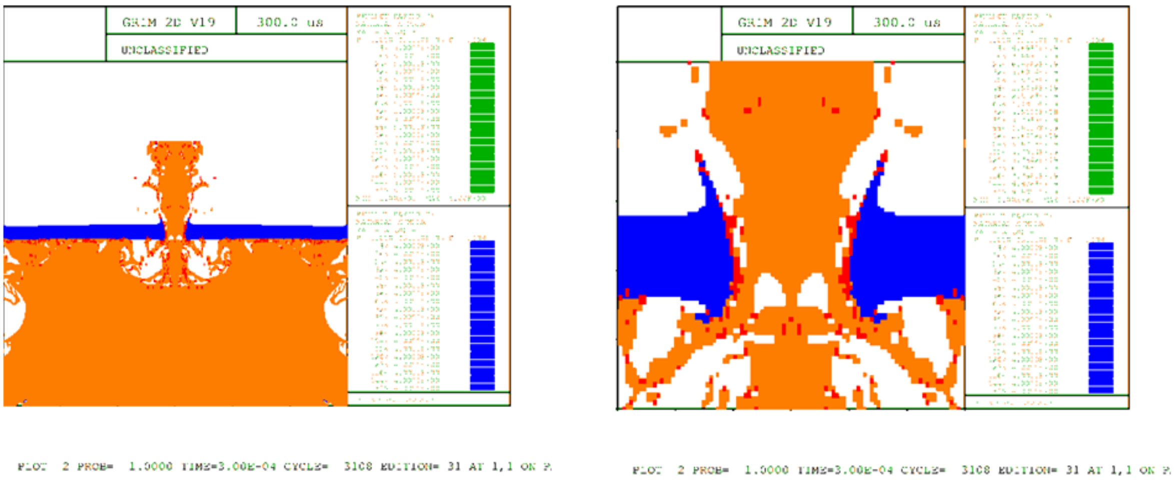

Figure 3.16: CSSJ penetration of RHA plate at 2CD stand-off

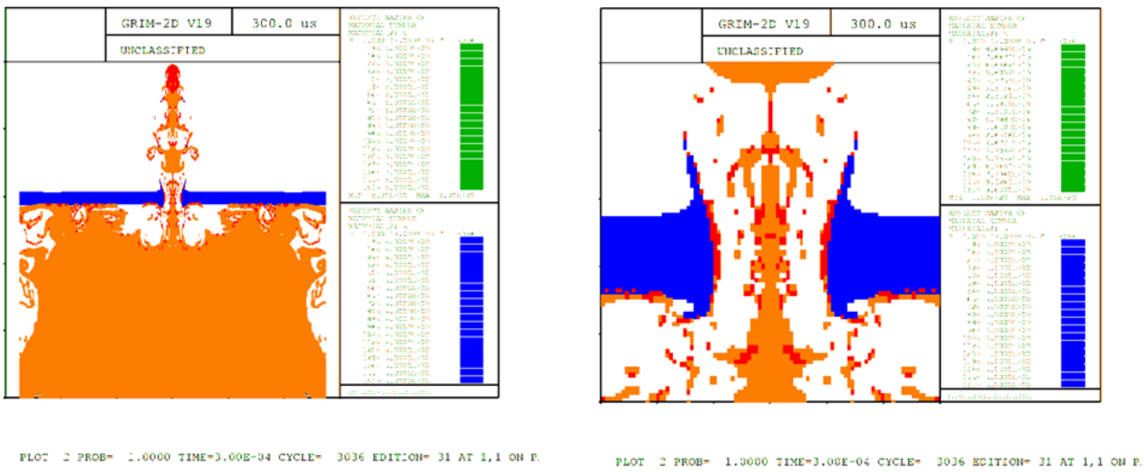

Figure 3.17: CSSJ penetration of RHA plate at 3CD stand-off

A similar exercise was undertaken with a concrete target, which represented the municipal structural target. Modelling of this projectile / target interaction was undertaken in 2D, since the resources required to model this interaction in 3D would have been significant and would have prevented further avenues of research from being pursued due to cost and time constraints. A semi-infinite target was used to observe the depth and width of crater that could be created by the CSSJ warhead. The target was not as sophisticated was the actual Municipal structure target, which is reinforced with perpendicular crossed steel bars to the front and rear of the wall. To ensure that the model would run in a reasonable time without sacrificing cell resolution, it was necessary to model in 2D half symmetry. Therefore the reinforcing bars were not included in this modelling phase[31]. The first model was run with the CSSJ warhead at 1CD stand-off and the plot of the hole profile in the concrete is shown in Figure 3.18.

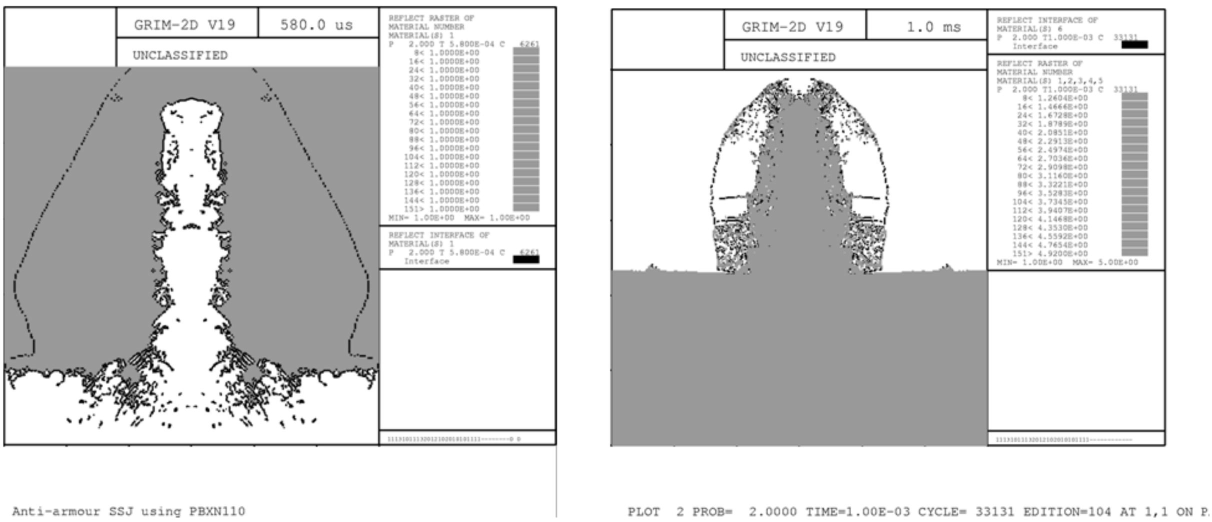

Figure 3.18: 1CD stand-off baseline (left) and CSSJ (right)

Following the analysis of these simulation series it was clear that the run time was significantly longer than that of the RHA target, which is linked to the use of a

[31] Concrete strength was increased to account for the lack of steel reinforcement

semi-infinite target. Therefore further modelling was constrained to a 3CD stand-off, which whilst leaving a gap in the understanding of warhead performance at 2CD, provided an upper bracket for performance at longer stand-offs that would be achievable within a missile system. As with the anti-armour modelling a comparison with the baseline warhead was performed. As no data existed on the baseline warhead against a semi-infinite concrete target it was also necessary to model the baseline warhead at 1CD and 3CD stand-offs. The plot for the 3CD run is shown in Figure 3.19.

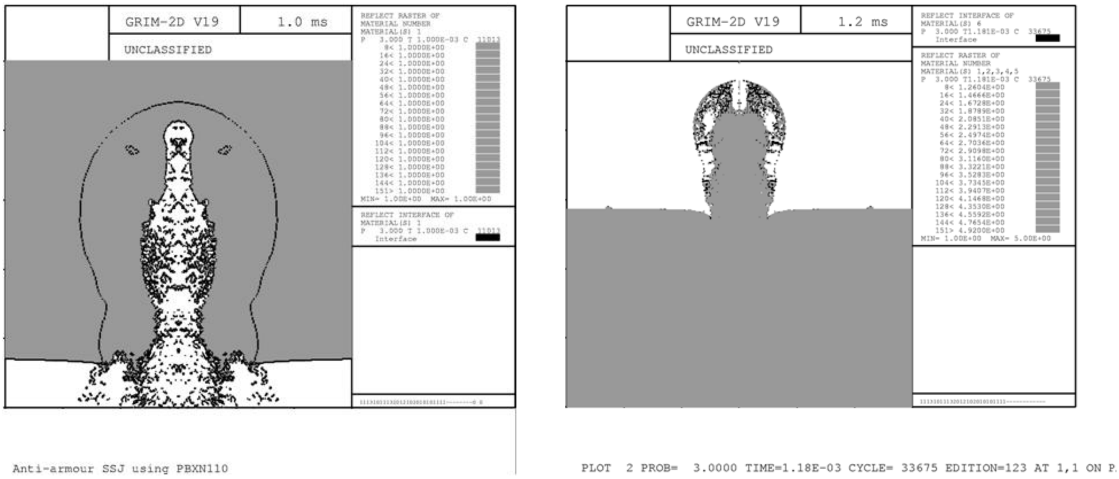

Figure 3.19: 3CD stand-off baseline (left) and CSSJ (right)

The analysis of the modelling phase is shown in Table 3.3 where the absolute values for various aspects of target damage are given.

Warhead Type	Explosive Filling	Stand-off (CD)	Bore Depth	Minimum Bore Diameter	Throat Diameter
			(% of Baseline at 1CD)		
Baseline	EDC1s	1	100	100	100
Baseline	EDC1s	3	138	79	111
CSSJ	ROWANEX 1001	1	102	180	210
CSSJ	ROWANEX 1001	3	128	330	185

Table 3.3: Analysis of the anti-structures concrete penetration modelling

The results shown in Table 3.3 are taken from measurements of the plots shown in Figures 3.18 and 3.19. It must be understood that whilst the depth of penetration is predicted with some confidence, the current concrete materials algorithm is unable to accurately reproduce the details of the surface crater around the throat of the bore hole. Modelling of a semi infinite target was therefore performed as modelling of a panel may produce some misleading results. Penetration of concrete panels can be dominated by 'free-surface' effects depending on how thick the panel is, as discussed in the paper by Chen X.W et al [76]. When a projectile impacts a concrete panel it creates damage around the impacted area, which can lead to extensive cratering. The same is true for the rear surface of the target, as the impact shock transmitted through the target material, is released from that surface to produce spall. As a result the two craters may cause significant damage to the target whilst the bore hole through the target may be very narrow. The need to create a large diameter borehole comes from the internal blast defeat mechanism that is required when attacking such a structure. A large borehole is required to allow the main warhead to pass into the target and detonate at an extended time delay. In a target where the formation of a crater to the front and rear creates a complex interaction, hydrocode modelling can only be predictive if the material model has been well validated over a series of several trials under different initial conditions. Close inspection of the plots shown in Figures 3.18 and 3.19 show a zone that has been cleared of target material with, surrounding regions that are indications of cracks and fissures. This may be an indication of cratering, however this is not an area where prediction can be confidently made. As stated above the concrete model can reliably predict used depth of penetration in a semi-infinite target. This approach was therefore used to provide a coarse comparison.

The results shown in Table 3.3 show that at 1CD stand-off the CSSJ appears to produce superior results to the baseline (an increase in crater volume of approximately 330%), although in terms of depth of penetration the improvement is marginal. Upon inspection of the projectile produced by the CSSJ warhead it can be seen that it is slightly thicker than the projectile produced by the baseline warhead, probably accounting for the predicted increase in damage to the target.

At 3CD stand-off the CSSJ does not penetrate as deeply through the target material as the baseline, but appears to be superior in other areas. The CSSJ produces a much larger crater in the target; this indicates that the levels of damage to the target will be far greater than that achieved by the baseline. This again is possibly a result of the increase in projectile diameter. Typically a high speed (8mm/μs) shaped charge jet would pass through a concrete target leaving a narrow hole and small craters to the front and rear of the target. It is possible that the 'de-tuning' of the warhead has optimised the effect against the target. Following some minor changes to the engineering aspects of the warhead design to reduce the warhead all-up mass, the design was taken forward to manufacture.

Further modelling was performed to understand how seeker elements such as batteries, radomes, circuit boards etc would affect the projectiles in the early stage of formation. When obstructions are placed in close proximity to the front of a shaped charge warhead the resulting jet or projectile will generally be adversely affected, with resulting asymmetry or early particulation, which would cause a loss in performance. The results of this phase of modelling cannot be discussed in this thesis; but the work was completed, with the recommendation that any precursor warhead must be integrated into the seeker to maximise potential performance benefits.

The second warhead option, the JC-EFP warhead was a variation on a Miznay Shardin type warhead, with the addition of a trumpet profile in the central section of the liner. As this warhead design was completely different to the baseline; it was therefore decided that comparison between the JC-EFP and baseline would have to be performed through experimental trials. It was thought that this completely different approach to target defeat may yield different target effects against the armour target, with the aim being removal of as much target material, thereby producing a greater level of behind armour debris. The main explosive filling of the JC-EFP was also Rowanex 1001 and the warhead design is shown in Figure 3.20. The liner was also manufactured with the same copper used in the CSSJ warhead, the production technique was similar to that of the baseline warhead liner, however the central trumpet section required that a very thick blank be pressed and the liner profile was then machined on a CNC lathe.

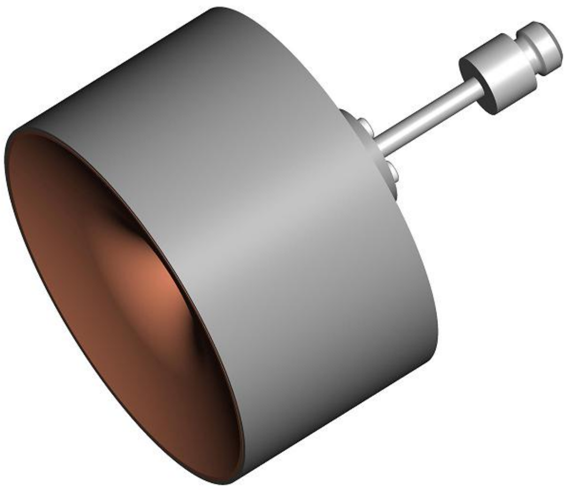

Figure 3.20: JC-EFP warhead

GRIM2D was used to model projectile formation and target interaction. The first modelling phase investigated projectile formation Figure 3.21.

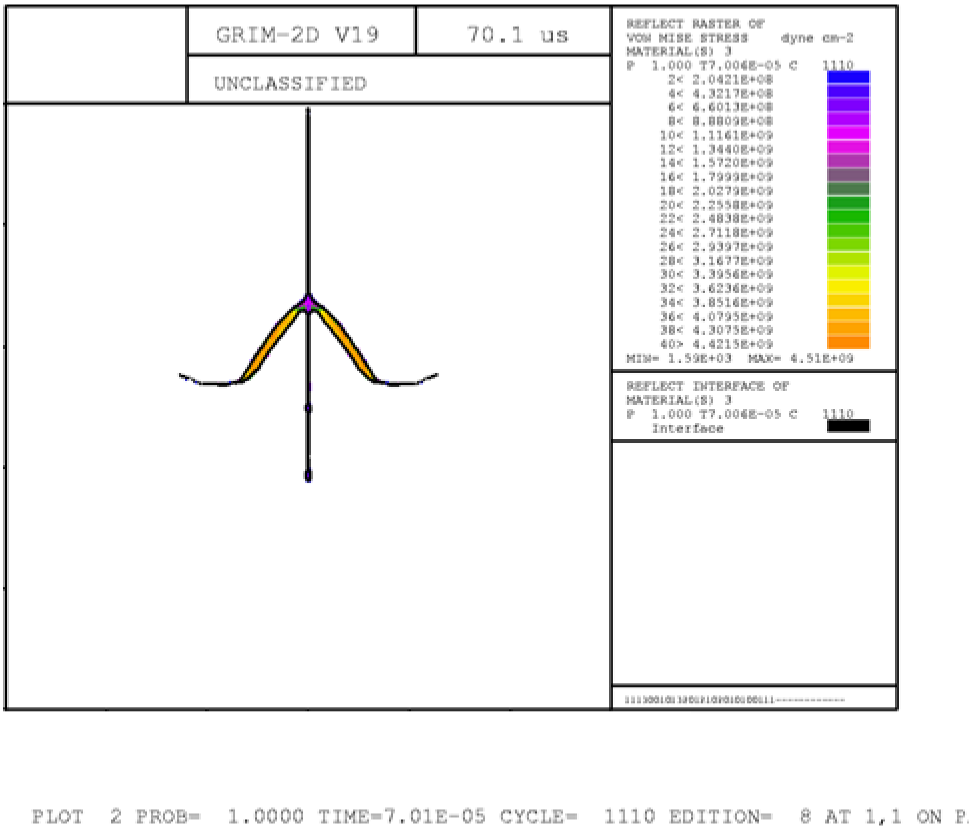

Figure 3.21: JC-EFP projectile plot

The JC-EFP has a large inflection in the pole of the liner, this design feature was included to assist in encouraging crack propagation through the Municipal Structures target as the rest of the liner would not be capable of producing a large crater in the target without some assistance. As a result the central 'trumpet' portion creates a 'jet' which travels in a velocity regime approximately 50% lower than that typical of a conical lined centrally initiated shaped charge. It is generally acknowledged that shear is the main perforation mechanism of this type of EFP, an effect that can be difficult to predict. However some indication as to performance can be made by observing the stress in the target.

To observe the performance against armour the hydrocode was used to predict penetration performance at various stand-offs and a plot at 1CD stand-off is shown in Figure 3.22.

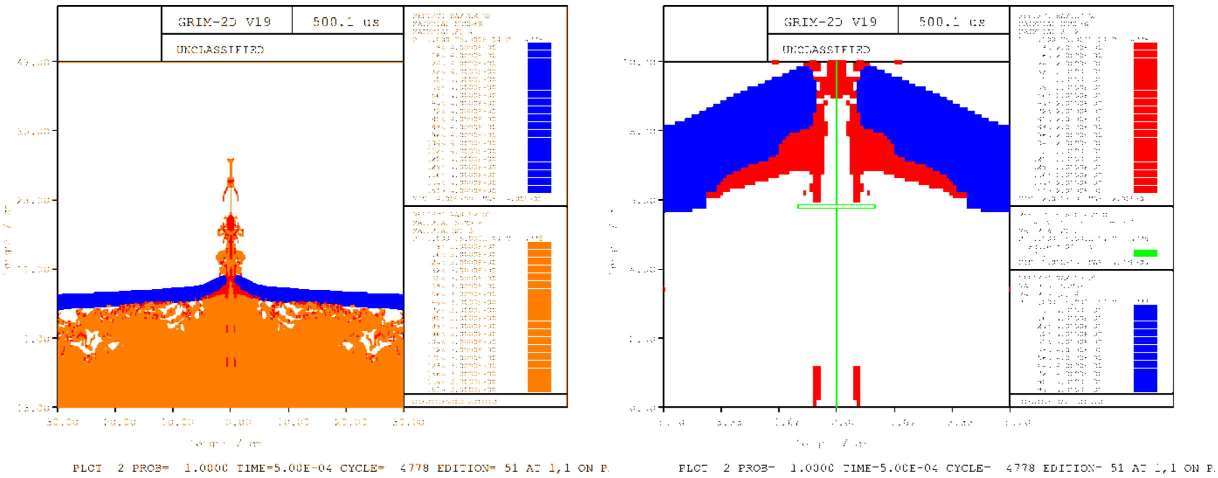

Figure 3.22: Final plot of 1CD stand-off (left) and zoomed plot (right)

The prediction from the model was that the armour would only be defeated by the central portion of the jet, whilst the remaining liner material would be defeated by the protective capability of the armour, although the armour appears to exhibit severe levels of damage. To better understand the reaction of the target it was necessary to carry out further analysis of the stress that the target was under. A plot of the Von Mises stress was undertaken to observe any indications of material yielding under high levels of pressure exerted by the projectile.

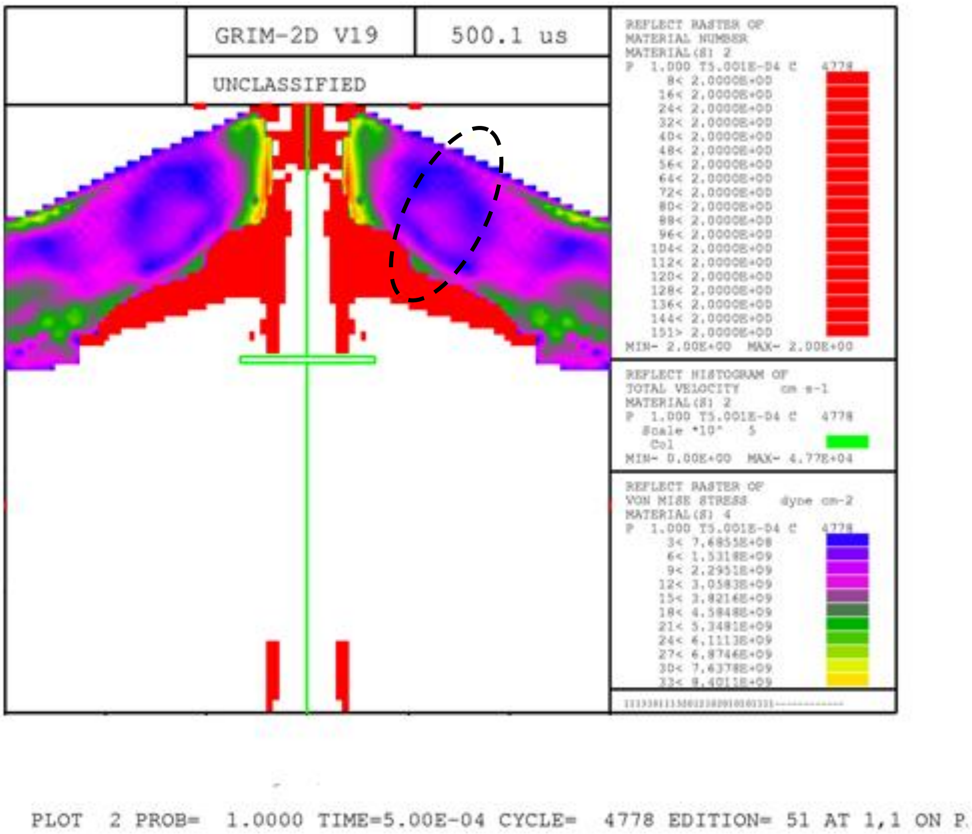

Figure 3.23: Von Mises plot of stress within the armour target

The plot shown in Figure 3.23 shows the regions of high stress in the armour target. The region surrounding the highly deformed area may well fail, however the pressure in the region which is plotted in blue (circled in Figure 3.23) is approximately 750MPa, with the yield strength of the armour plate being approximately 1.3 GPa, therefore fracture may not occur. The armour material model did not contain a fracture model, the hydrocode would treat this issue numerically, i.e. it would allow the target material to stretch on continuously.

Anti-structures modelling was performed at 1CD and 3CD stand-offs to observe how effective the JC-EFP would be at penetrating the semi infinite concrete target. The plots of the final positions of the projectiles can be seen in Figures 3.24 and 3.25.

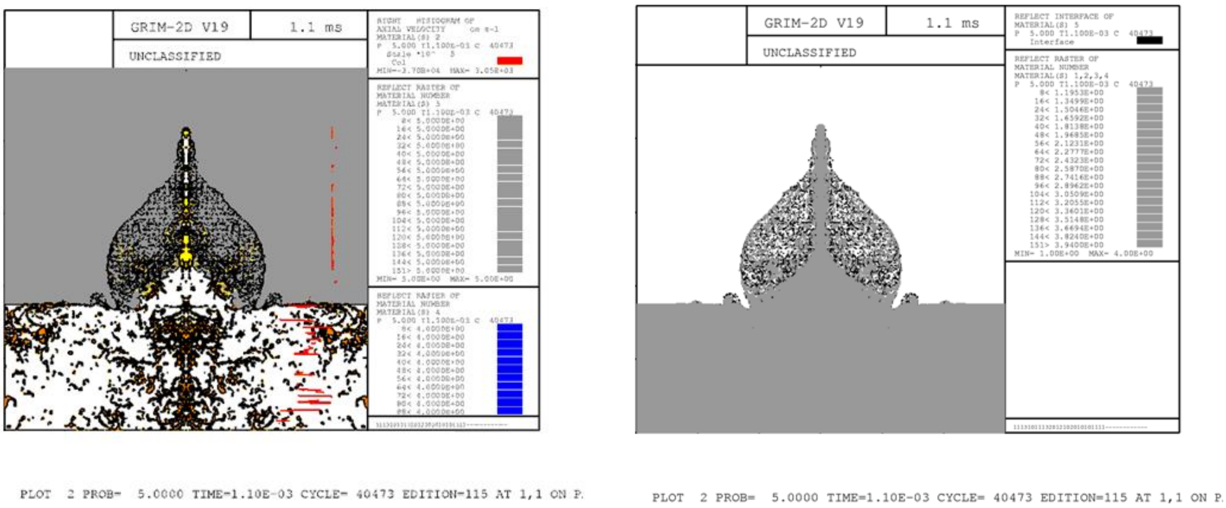

Figure 3.24: JC-EFP plots at 1CD stand-off

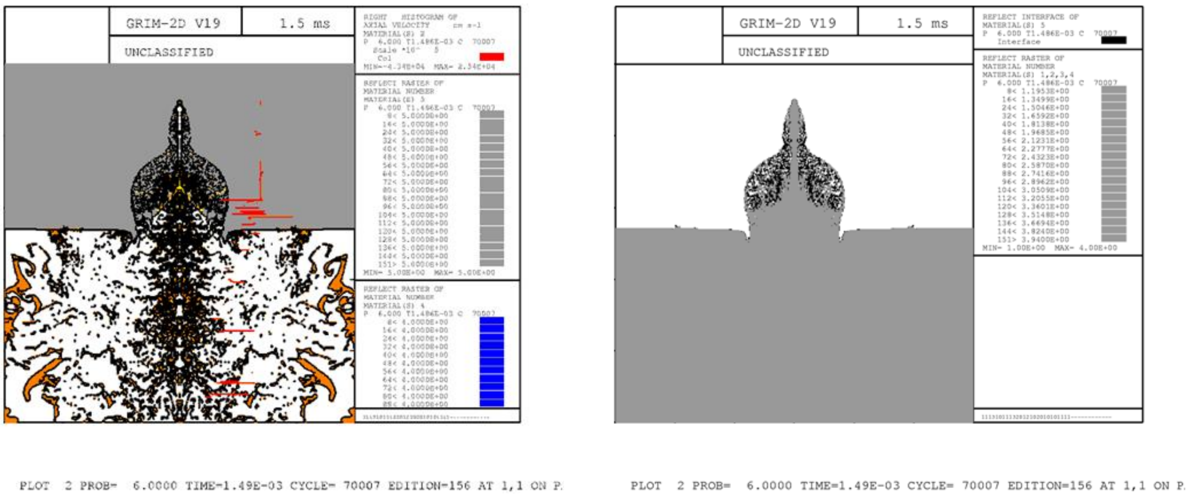

Figure 3.25: JC-EFP plots at 3CD stand-off

The analysis of the modelling phase is shown in Table 3.4 where the absolute values for various aspects of target damage are given.

Warhead Type	Explosive Filling	Stand-off (CD)	Bore Depth	Minimum Bore Diameter	Throat Diameter
			(% of Baseline at 1CD)		
Baseline	EDC1s	1	100	100	100
Baseline	EDC1s	3	138	79	111
JC-EFP	ROWANEX 1001	1	128	75	285
JC-EFP	ROWANEX 1001	3	107	120	340

Table 3.4: Analysis of the anti-structures concrete penetration modelling of the JC-EFP

Close inspection of the plots shown in Figures 3.24 and 3.25 show a zone that has been cleared of target material, surrounded by material containing indications of cracks and fissures, the same mechanism that was observed when modelling the CSSJ warhead. The profile of the crater and the damaged zone surrounding it is very different to that seen in the SSJ and CSSJ plots, due to the completely different nature of the formed projectile. The CSSJ produces a cylindrical projectile which penetrates the target in a manner similar to a kinetic energy rod, as discussed in detail by Stubberfield et al [77]. However the JC-EFP produces an unusual projectile which has a large Miznay Shardin type dish shaped portion and a very narrow and much higher speed jetting central portion. Upon inspection of both plots it is clear that the crater profile is very similar, with an extended damaged zone surrounding it. The central jetting potion of the projectile has produced, as expected, a narrow deep penetration into the target, when compared with the damage caused by the main body of the projectile. It was also expected, however, that the damaged zone (crack propagation) surrounding the crater would be extensive. The jetting portion was expected to exert pressures in the region of 5GPa which would cause extensive damage. The plots, however, seem to suggest that this phenomena is not present. This may lead to the projectile not defeating the target at 90° or 45° obliquity.

At 1CD the JC-EFP produces a crater which is conical in nature, with an included angle from mouth to apex of approximately 100°. The jetting portion of the projectile has produced a bore hole in the target which is very narrow, extending deep into the target. The damaged zone surrounding the target is extensive. Should this prediction actually point to failure of the target material it is expected that the target would fail at 90°. However defeat of the target at 45° obliquity cannot be guaranteed as the phenomena being investigated (the damaged zone within the target) is not well characterised.

At 3CD stand-off the JC-EFP's penetration of the target material was commensurate with that at 1CD stand-off. However close inspection of the initial portion of the crater shows that the mouth to apex angle, as shown in Figure 3.26, has increased significantly from approximately 100° to approximately 150°. This may be related to the geometry of the projectile upon impact. The initial crater is also recessed into the target unlike that seen at 1CD stand-off where the mouth of the conical crater is flush with the target surface. At this stand-off the JC-EFP appears to remove more material from the target, although the damaged zone surrounding the target appears to be reduced, suggesting a trade-off in performance between the two stand-off distances.

The hydrocode model has predicted that the JC-EFP warhead is capable of producing wide holes in armour targets (with some interpretation of the plotted results) and is also capable of producing wide holes in a concrete target. The depth to which the JC-EFP can penetrate the concrete target is dominated by the jetting portion. It was therefore expected that this would create extensive damage throughout the target, which could be exploited by the kinetic energy of the remaining portion of the projectile. Analysis of the plots from the concrete modelling, however, appears to demonstrate that the case for this hypothesis may be marginal. Any analysis of the damaged zone surrounding the crater must be treated with caution due to a lack of sufficient data on the phenomena. Further trials work with this design of warhead was considered to be the most suitable way of fully understanding its terminal effects characteristics. No changes were made to the warhead design prior to manufacture.

When the JC-EFP was compared to the baseline SSJ warhead, it was deemed that the JC-EFP may produce a wider hole in the armour target. It was clear that this may be the extent of the warhead performance, with little performance in hand to enable target defeat at other obliquities or stand-offs. The performance against concrete is clearly very different with interpretation of the model concluding that if the damaged zone were to contribute to the penetration performance of the JC-EFP that it would be a preferable option to the baseline warhead.

3.5 Follow Through Bomb / Main Charge Design

Crew Served and air launched ATGWs are generally designed to defeat heavy armour targets, but in a changing climate where Joint Rapid Reaction Forces are expected to deploy quickly and fight in a very dynamic environment, weapons that are inflexible in their design cannot offer a complete capability. An extension of the 'tandem follow through concept' which was described in the background chapter was pursued. The general arrangement of a suitable warheads system for the Javelin and Brimstone missiles can be seen in Figure 3.26.

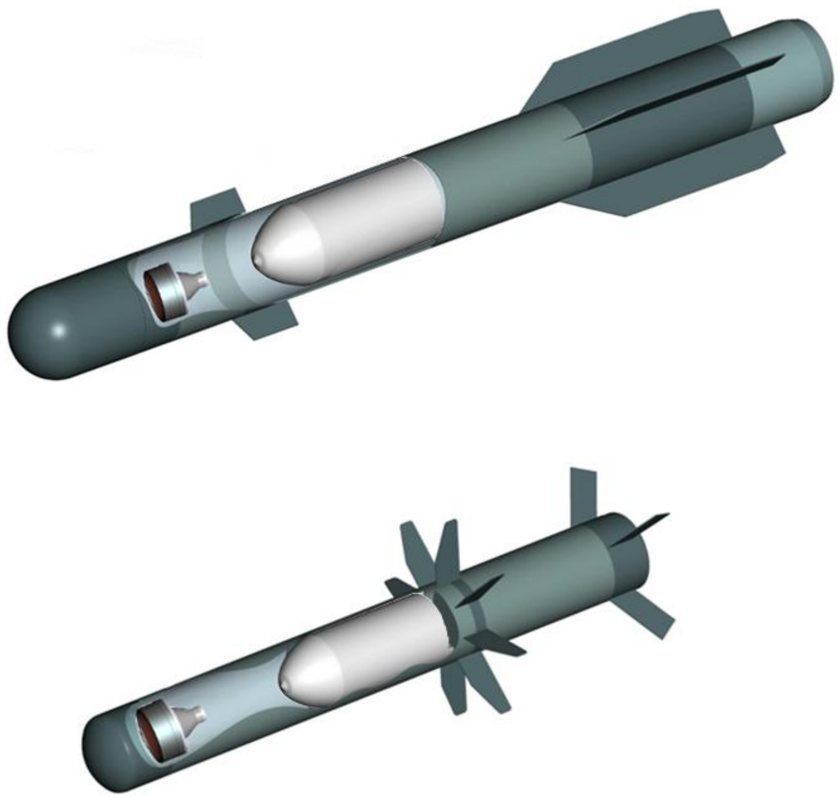

Figure 3.26: Precursor and FTB/MC concept, Brimstone (top) and Javelin (bottom)

The use of less vulnerable explosive materials was also pursued in design of the FTB/MC, thereby informing on the ability to lower vulnerability for storage, carriage, and use in the battlefield. To enable defeat of such a wide spectrum of targets the main charge had to be capable of penetrating the base armour of the threat MBT, and must also possess some KEP (Kinetic Energy Penetration) capability, enabling it to enter structural targets where it could detonate after an extended time delay. A third charge could also be used in instances where emplacement of an explosive charge inside armoured targets was required. This concept was briefly considered, however it was clear that such an intermediate device would probably not survive detonation of the precursor without significant protection. To support the FTB/MC warhead design work, the GRIM2D and DYNA 3D[32] modelling tools were used. These provided a basis for design of the precursor warhead design and provide indications of the ability of the FTB/MC to survive precursor detonation and target interaction. The performance requirements of the FTB/MC were determined, being based on the various protection levels of the vehicle targets as a function of attack angle and the performance capability of the precursor. It was also necessary to determine if any trade-offs existed between the calibre, mass and performance of the rear charge when incorporating a KEP capability to the design to provide an emplacement function for the attack of thin armour and structural targets.

To ensure that the FTB/MC would produce levels of penetration which would be commensurate with protection afforded to the frontal arc of an MBT the shaped charge design was partially based on the main warhead in the QinetiQ tandem shaped charge warhead system, the main charge shown in schematic in Figure 3.27.

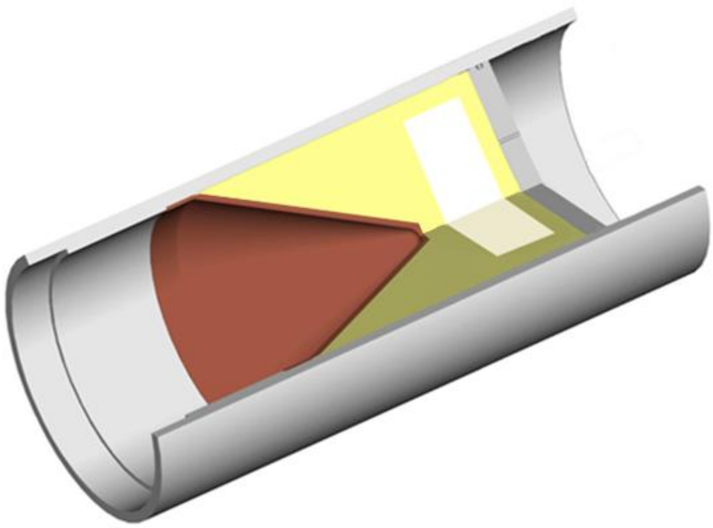

Figure 3.27: QinetiQ peripherally initiated warhead (schematic approximation)

[32] DYNA is a Lagrangian code, to predict material response a mesh is mapped over the components, GRIM is an Eulerian code, to model material response a single mesh (within which all material reside) is used.

The QinetiQ shaped charge warhead provided the baseline for shaped charge performance. The initial design of the FTB/MC was based on the FTB warhead in the UAW as presented by QinetiQ at AUSA 2006, Figure 3.28. The aim of the design programme was to place the QinetiQ shaped charge warhead design inside an FTB similar to that of the UAW FTB profile.

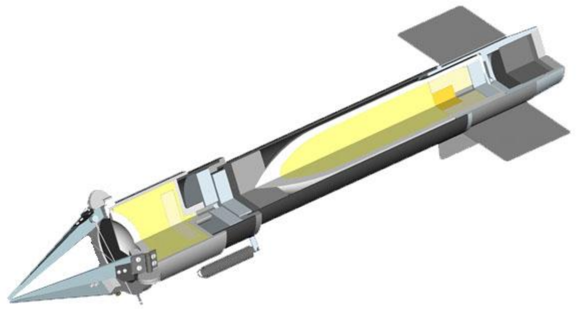

Figure 3.28: QinetiQ UAW tandem projectile (exploded view)[33]

The selected main explosive filling for the FTB/MC was PBXN-110. It was chosen as it is a low vulnerability explosive and used in many other explosive systems. It was also thought to be comparatively more rigid than other PBX formulations. This additional rigidity was thought to aid machining of the waveshaper cavity to the required geometric and positional tolerances. As an explosive with reduced detonation pressure was to be used as the main filling, some changes to the width of the waveshaper were required, thereby making the initiation angle more aggressive, as illustrated in Figure 3.29.

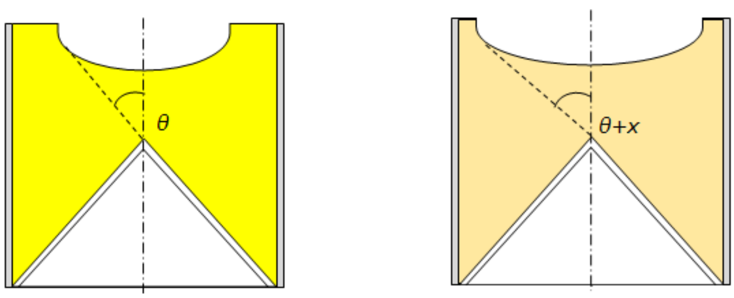

Figure 3.29: Initiation angle optimised for EDC1s (left) and PBXN-110 (right)

[33] Image courtesy of QinetiQ (AUSA presentation material)

As can be seen in Figure 3.30, the FTB/MC features an ogive that is part of the casing of the warhead. The first hydrocode modelling task was to investigate the effects of the ogive on the shaped charge jet.

Figure 3.30: Side view of the FTB / MC

The QinetiQ tandem warhead research design was used to inform design shaped charge element of the FTB/MC and as PBXN-110 had previously been used in that warhead design therefore characterisation of the warhead without the ogive was unnecessary. The use of an ogive was required for two reasons. For emplacement, the interaction of the FTB/MC with structural and thin armour targets requires an ogive to maintain the structural integrity of the warhead for extended time delays to be achieved. Secondly, with the precursor detonating several hundred microseconds before the main charge, fragments and blast are thrown back toward the main charge. An inter-charge barrier is typically used to protect the main charge from this. However, the use of an ogive provides the same protection and can therefore replace the normal flat plate inter-charge barrier.

DYNA 3D was used to investigate the interaction of the FTB/MC ogive with RHA of a thickness that represents LAFV (Light Armoured Fighting Vehicle) targets. The aim of this modelling phase was to demonstrate the capability of an FTB/MC to pass through the target with a hole 90% of the FTB/MC calibre. Figure 3.31 shows that the initial design, with a casing constructed from high strength steel, failed to pass through the target, with massive levels of failure being observed where the ogive meets the parallel section of the case.

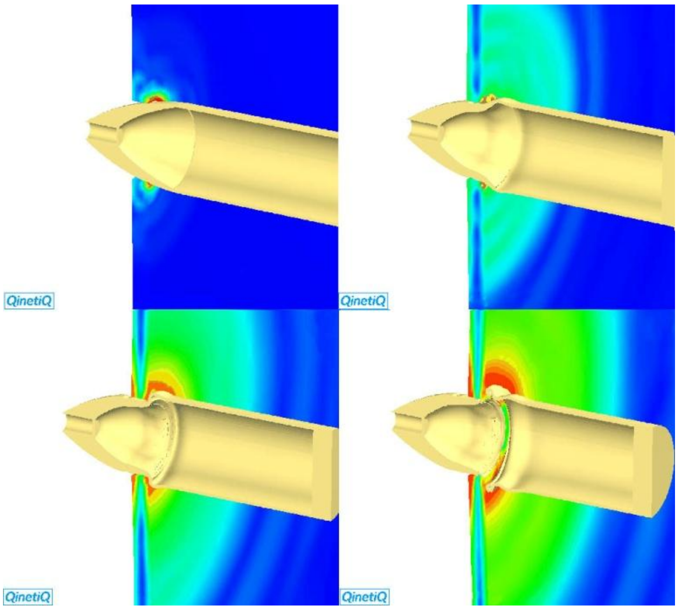

Figure 3.31: Initial FTB design failing to defeat LAFV armour target

Following this modelling exercise, several iterations of ogive design were considered. Figure 3.32 shows the most successful design that was modelled. It was clear that although the model indicated that the warhead could pass through the target, the explosive filling would be severely disrupted and any fuze elements would be ejected from the rear of the warhead. In addition the extra mass required in the ogive to defeat the target meant that the warhead mass would be well above typical main warhead mass for the Javelin and Brimstone missiles, the mass of the Brimstone main charge explosive content is quoted in Jane's International Defence Review [78].

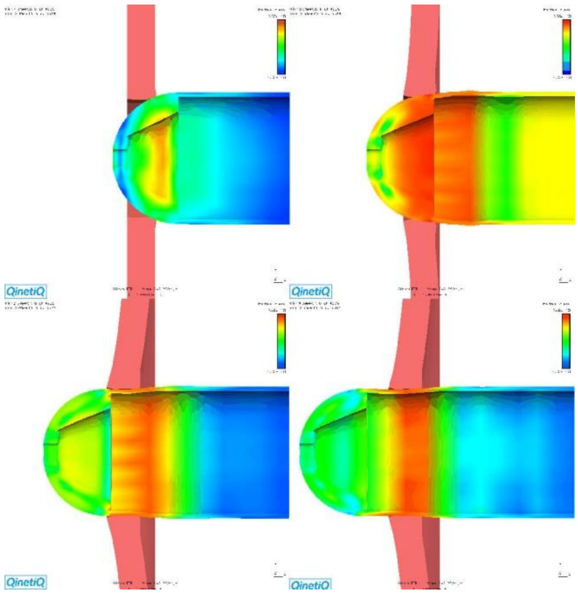

Figure 3.32: Ball nosed FTB passing through LAFV armour target

It was therefore decided that emplacement into LAFV targets was not a viable solution as it could only be achieved through use of a smaller calibre FTB/MC. It was realised that defeat of LAFV targets would still be achieved through the more traditional tandem shaped charge attack. Therefore this approach was not pursued. Despite this, a light ogive design was considered capable of defeating any remaining armour (following attack from the precursor) and when interacting with thinner armour that is present on soft skinned vehicles such as IADS (Integrated Air Defence Systems) vehicles and SSM (Surface to Surface Missile launchers).

The presence of an ogive at the front of the FTB/MC meant that the shaped charge performance would be slightly reduced as the jet would need to penetrate it before penetrating the target. It was also thought that there could be some issues regarding gas confinement in the ogive that may have caused disruption of the jet as it passed through the small hole it had produced in the ogive. To investigate these issues it was necessary to use the hydrocode to model the warhead design. Initial modelling showed that gases trapped within the ogive had impinged on the jet as it developed, resulting in the 'gas guillotine effect'. Figure 3.33 depicts the disrupted jet passing through a long channel at the apex of the ogive of the FTB/MC.

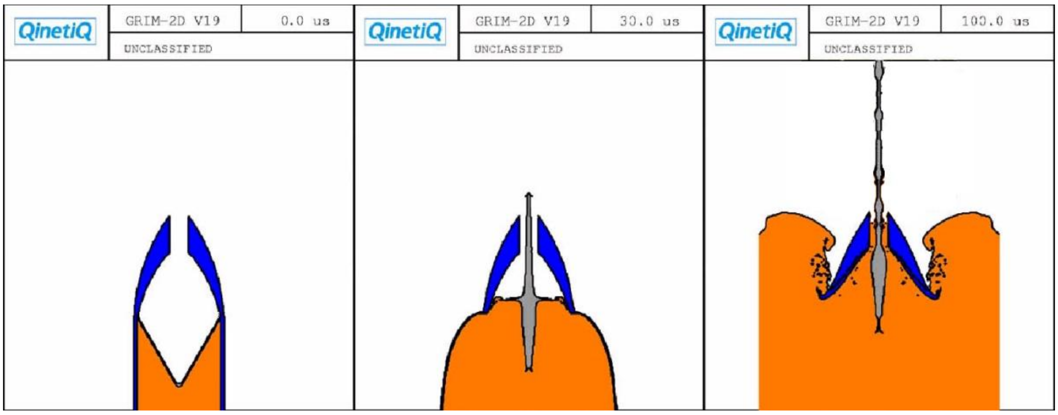

Figure 3.33: Steel cased FTB/MC with long channel (PBXN-110 filling)

Subsequent modelling demonstrated, with a reduced channel length through the ogive, that the effect could be drastically reduced, in Figure 3.34. This design produced a jet with a tip speed 5% less than that of the QinetiQ shaped charge in an aluminium case and filled with EDC1S. This reduction in tip speed was considered to be acceptable.

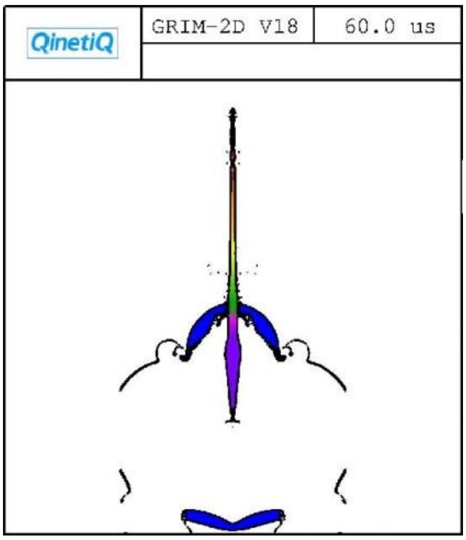

Figure 3.34: Steel cased FTB/MC with reduced channel (PBXN-110 filling)

The mass of the warhead was still considered to be significantly over the indicative mass budget and further modelling was performed to reduce the mass of the warhead whilst maintaining the shaped charge jet characteristics.

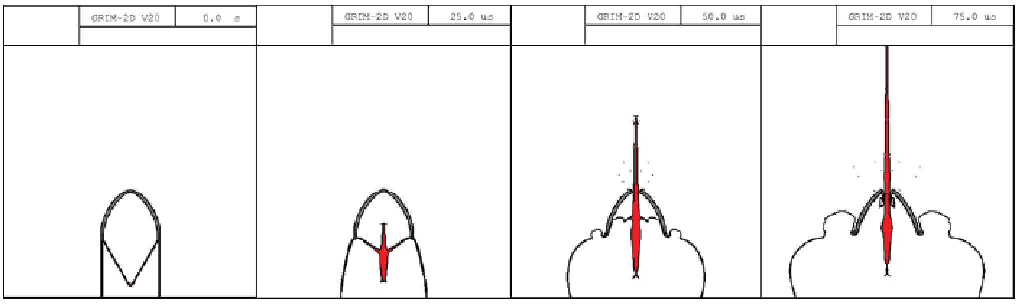

Figure 3.35: Steel cased FTB/MC with reduced ogive profile (PBXN-110 filling)

Further modelling predicted that a much lighter weight ogive would not unduly affect the shaped charge jet and as the decision had been made to not include emplacement within medium armoured vehicles, a reduction in ogive mass was an acceptable design change, the plots from this model can be seen in Figure 3.35. Following a succession of modelling studies – including tandem interaction which is discussed in Chapter 5 - a single warhead design for the FTB/MC was derived, shown in Figure 3.36. The apex of the ogive consists of a raised section which is thinned down to aid shaped charge jet survivability. The profile of the raised portion was changed after iteration 10 of the survivability modelling phase as it appeared to be close to failure.

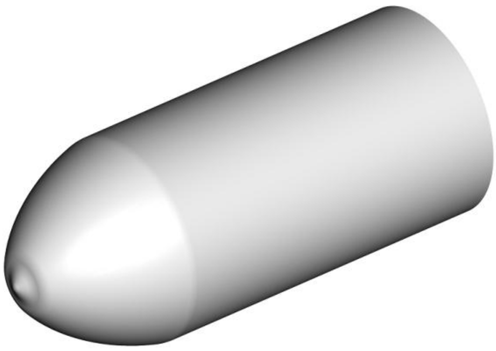

Figure 3.36: FTB/MC final design

The resultant warhead design required a single piece warhead casing to be turned from a solid billet steel. Normally in a large scale manufacture process this would be forged and then finish turned, however in the scale of manufacture commensurate with experimental work forgings would not be economical. The copper liner was typical of a precision warhead liner design and the same manufacturing processes were, therefore, adopted with, a high purity copper blank turned into a disk from a square plate and then flow formed over a suitable mandrel. The flow forming process, which is illustrated in Figure 3.37, not only produces the near net shape of the liner but also applies significant mechanical cold working to the material, a 50% reduction in material thickness is typical, thereby reducing the grain size of the copper liner. Recrystallisation is required following this process to achieve a homogenous grain structure.

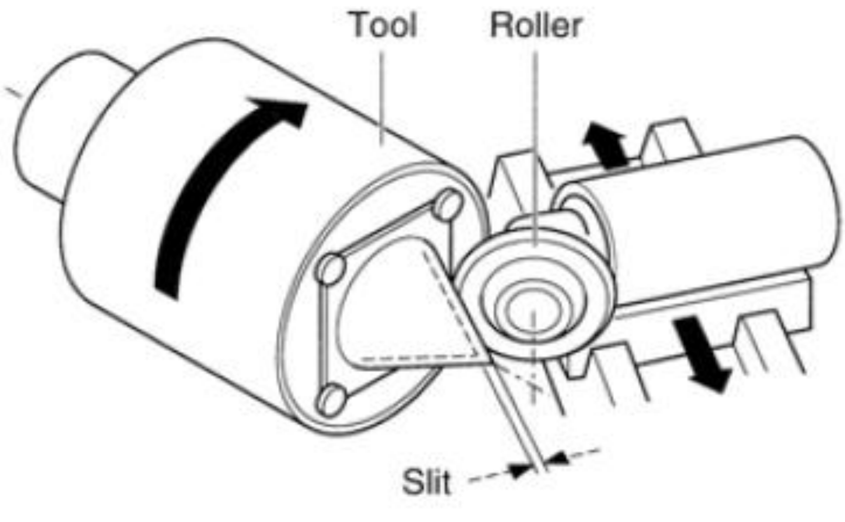

Figure 3.37: Flow Forming of Copper liner (image courtesy of Prof Manfred Held TDW)

To ensure that grain size is regular a further heat treatment cycle is applied, to aid jet formation as a heterogeneous structure encourages early jet particulation.

3.6 Summary

The requirement to defeat an ever increasing target set with fewer variants of weapon system places a significant emphasis on coupling of effects in a manner that has not been previously explored. The breadth of targets discussed in this chapter was significant, as such the use of the entirety of conventional warhead effects, which were discussed in Chapter 2, were considered.

The warhead system design was driven by the need to exploit the technology within suitable candidate missile systems such as Brimstone. Therefore emphasis was placed on achieving a warhead system mass which would be commensurate with the available subsystem mass.

The design of the warhead system was informed through an extensive hydrocode modelling study. The study investigated design of a precursor warhead, and a main charge. The initial warhead designs were based on previous work which focussed on two distinctly different areas, the defeat of armour and the defeat of structures. The modelling predictions provided indications that a suitable compromise could be achieved. The modelling work also indicated that if emplacement of the main charge into the LAFV target were required, the precursor warhead would need to generate a through hole diameter which would be the same or greater than the diameter of the FTB/MC. This requirement was therefore no longer pursued as it was deemed unnecessary as defeat could be achieved without emplacement.

The hydrocode modelling study indicated that the two designs of precursor warhead were suitable for testing in live trials, along with single FTB/MC design.

Chapter 4
Multiple Effect Weapon Warhead System
Live Experimental Trials

This chapter will detail the experimental live trials performed on the MEW warhead system warhead components. Trials were undertaken to observe performance characteristics against various targets. In each case the warheads were trialled singularly. A tandem firing was not performed as tandem integration was not funded within the research programme, preventing observation of charge interaction. This chapter first describes the trials performed to characterise the precursor warhead, initially fired against RHA targets, at long and short stand-offs. A precursor warhead design was then trialled against two example ERA targets at representative system stand-offs. Finally the precursor warhead was trialled against the Fortified urban structure and the Municipal structure at 90° and 45° obliquities, at stand-offs that would bracket the Javelin and Brimstone missile systems precursor stand-offs. Also described in this chapter is the characterisation of the FTB/MC warhead, trialled against RHA blocks at various stand-offs to obtain an indication of possible performance values.

As part of a series of trials the warheads were fired against armour and structural targets. The first trial was performed in the Old Fort Bomb Chamber facility at Fort Halstead. Two warhead calibres were tested, with the larger warhead being 20% larger in calibre. Non-essential dimensions such as the rear casing thickness and the booster pellet casing were not increased in size. The first trial was focussed on defeat of armour representative of light armoured vehicles.

The workshop facilities at QinetiQ Fort Halstead manufactured and inspected all of the warhead components prior to assembly. Following this the assemblies were shipped to the industrial partner who supplied explosive filling services. To ensure that the lowest practicable level of insensitiveness could be achieved Rowanex 1001 was employed as the explosive filling. As resources were limited on this research programme the use of insensitive booster materials such as HNS (Hexanitrostilbene) could not be investigated. Instead EDC8 was used as it provided an expedient, cheap and reliable solution. The built up warheads can be seen in Figures 4.1 and 4.2.

Figure 4.1: CSSJ liner profile (left) and built - ready to fire (right)

Figure 4.2: JC-EFP liner profile (left) and built - ready to fire (right)

As can be seen from Figures 4.1 and 4.2 there is a significant difference in warhead construction and liner profile, with the CSSJ being more complex in design and the JC-EFP incorporating a liner which has a large inflection in the centre.

4.1 Precursor Experimentation

Following filling, three trials were performed to examine the ability of the warheads to defeat a wide variety of targets; the trials are listed in Table 4.1.

Trial	Facility	Targets
Anti-armour	QinetiQ Fort Halstead – Old Fort Bomb Chamber	RHA plate – typical of medium armour
		RHA plate – typical of heavy armour
		ERA – typical of heavy armour
Anti-structures	QinetiQ Shoeburyness – Foulness Island	Fortified urban structure
		Municipal structure

Table 4.1: Trials performed

In the first trial several warheads were fired at RHA targets to understand the characteristics of the warheads and analyse their output. It was first necessary to perform firings at long stand-offs to enable radiography to be employed to study projectile behaviour in free space. The radiographs of the CSSJ and JC-EFP can be seen in Figures 4.3 and 4.4.

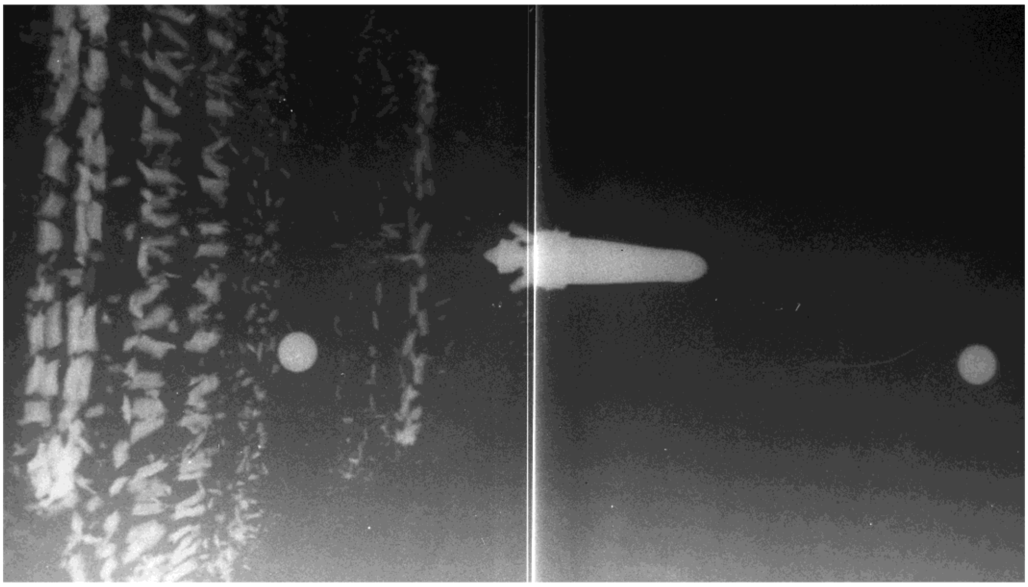

Figure 4.3: CSSJ 100μs

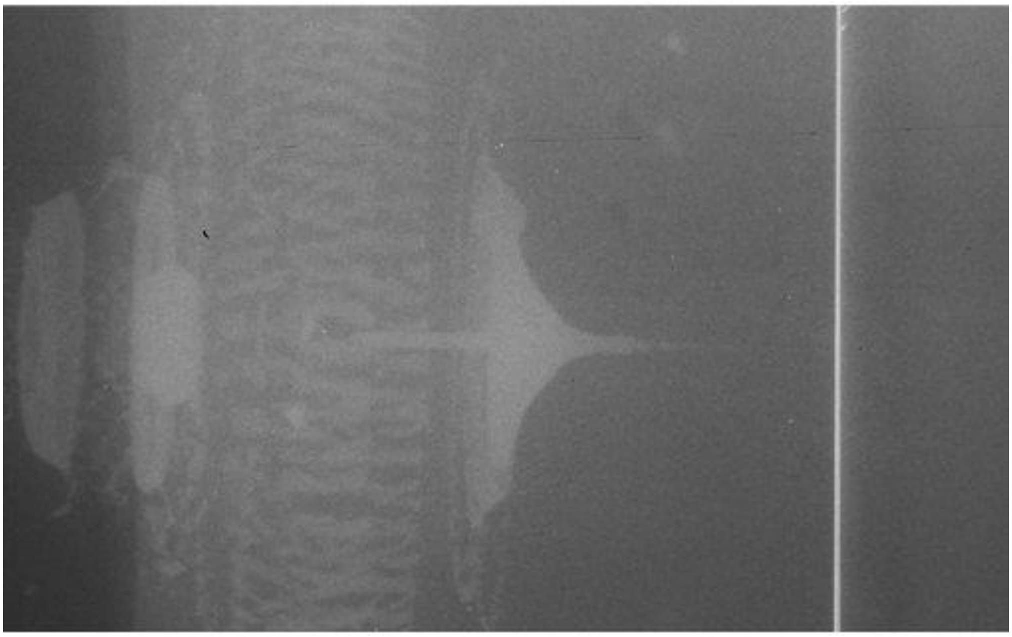

Figure 4.4: JC-EFP 50μs

In each image case fragmentation is clearly seen to the left side, whilst the projectiles can be seen in the middle of the film. It is clear in Figure 4.3 that a large single rod-like projectile has been formed, whereas the projectile formed in Figure 4.4 is wide with a stretching jet-like central portion. The jet-like portion results from the large inflection in the centre of the copper liner, in the same way as a traditional conical liner would do. The remaining portion of the liner, however, has not stretched and instead it has deformed in the same manner as a Miznay Schardin type liner.

When compared to the modelling it can be seen that there is very good agreement on the geometry of the projectiles. Figure 4.5 shows the geometries of the projectiles are relatively similar to those predicted by the numerical simulations. In the case of the CSSJ however, the hydrocode predicts that the rear portion of the projectile will remain attached, whereas the experiment shows that it detaches. This has little effect on target interaction as it appears to not be stretching the projectile and thereby not causing it to become unstable and particulate.

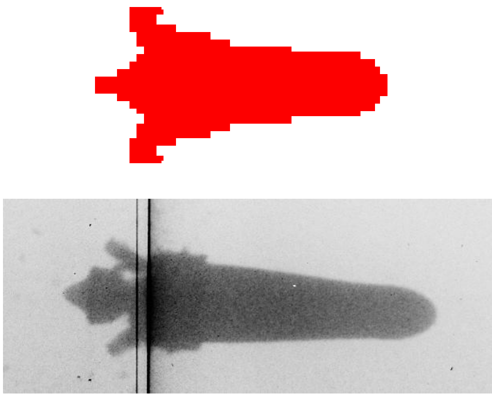

Figure 4.5: Comparison of CSSJ model (top) and experiment (bottom) at 100μs

The prediction of the formation of the JC-EFP is also very similar to the results seen in the trial, although the geometry of the radiographed projectile may look dissimilar to those that are unfamiliar with radiography and model interpretation. The plot shown in Figure 4.6 represents a half symmetry view of the projectile, i.e. a sectioned view. In the case of both models the prediction of velocity compared very well with the trials.

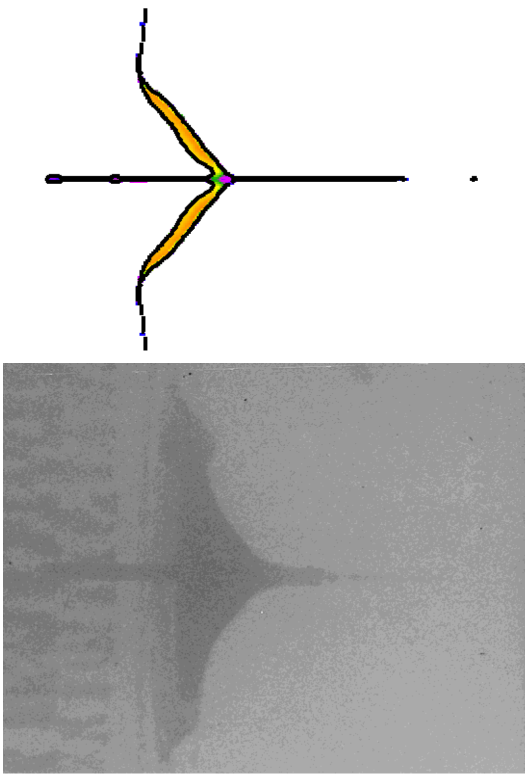

Figure 4.6: comparison of JC-EFP model (top) and experiment (bottom) at 50μs

Six warheads were fired at the medium armour target at 1CD stand-off at 90° and 45° obliquities, representative of the expected stand-off distance should the warheads be incorporated into a guided missile system. The first firings were performed at 1CD stand-off, 90° obliquity. Figure 4.7 shows a typical setup for some of the firings, although these firing were performed at greater stand-offs for diagnostic purposes. The perforated RHA plates for the 1CD firings are shown in Figures 4.8 and 4.9.

Figure 4.7: The CSSJ (left) and the JC-EFP(right) prepared for firing

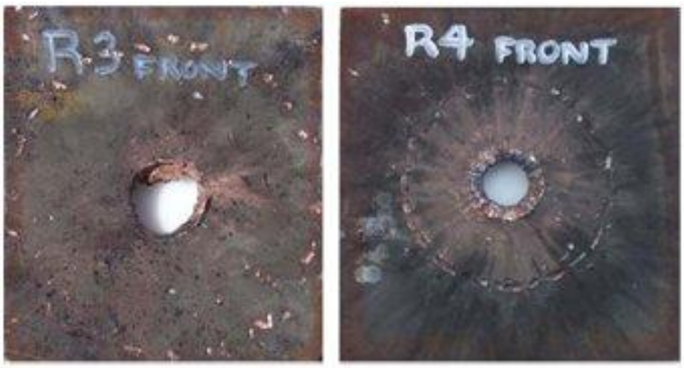

Figure 4.8: Medium armour RHA target perforation 1CD stand-off 90° obliquity, JC-EFP (left) and CSSJ (right)

Figure 4.9: Medium armour RHA target perforation 1CD stand-off 45° obliquity, JC-EFP (left) and CSSJ (right)

At 1CD stand-off, 90° obliquity, little difference in performance was seen between the baseline and the CSSJ, with both warheads achieving a hole diameter of the same magnitude. This was similar to the prediction calculated by GRIM2D. The JC-EFP produced a much larger hole than was predicted at 90° obliquity, achieving a hole diameter of 145% of the SSJ baseline, compared to the hydrocode prediction of 34%, although interpretation of the damage suggested in the hydrocode prediction that a much larger hole would be produced. The CSSJ also perforated the RHA target at 45° with a hole width (at its narrowest point) of 90% of the SSJ baseline. At 90° obliquity the JC-EFP was able to perforate the target, however, as suspected from the results of the hydrocode modelling at 45° obliquity, the main portion of the projectile was unable to defeat the target. The jetting portion perforated the target with a hole width, at its narrowest point of only 3% of the SSJ baseline. The difference in material path length was not significant (given the nature of the target), suggesting that this warhead would be performing at its limit when fired against the medium armour target at 1CD stand-off, 90° obliquity.

To better understand what was happening during the projectile formation and target interaction radiography was employed to observe the results of the experiments. The radiographs shown in Figure 4.10 are those taken of the CSSJ warhead perforating the RHA plate target from a 1CD stand-off. Following analysis of the radiographs it was clear that the CSSJ has overmatched the target to a large degree. The final radiograph shows the projectile still intact following perforation of the target with the projectile surrounded with spall (material from the target which has been ejected due to fracture). The spall cloud provides a significant secondary defeat capability. Although the spall produced by the CSSJ perforation was not measured, it is evident that this material would have some effect on the stowed ammunition inside the vehicle being engaged.

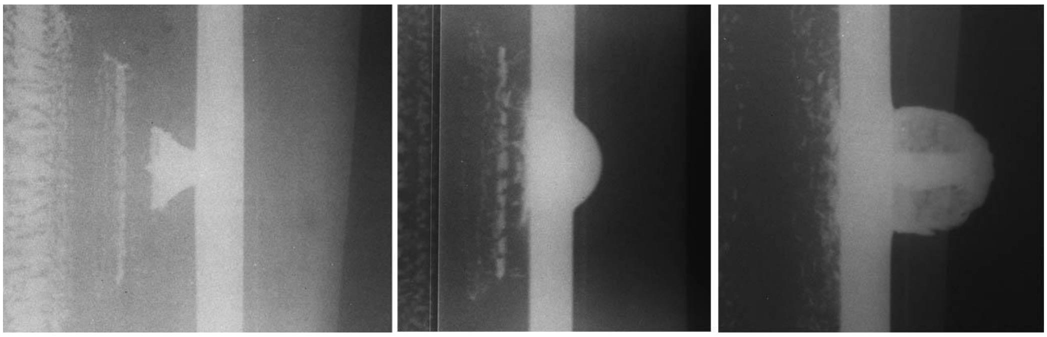

Figure 4.10: Radiography of CSSJ perforating the medium armour RHA target, (left to right) 61μs, 81μs, and 101μs

The JC-EFP did not perforate the RHA target at 45° obliquity to the extent that the CSSJ had, although it did perforate the target at 90° obliquity. Figure 4.11 shows the JC-EFP perforating the target at 90°.

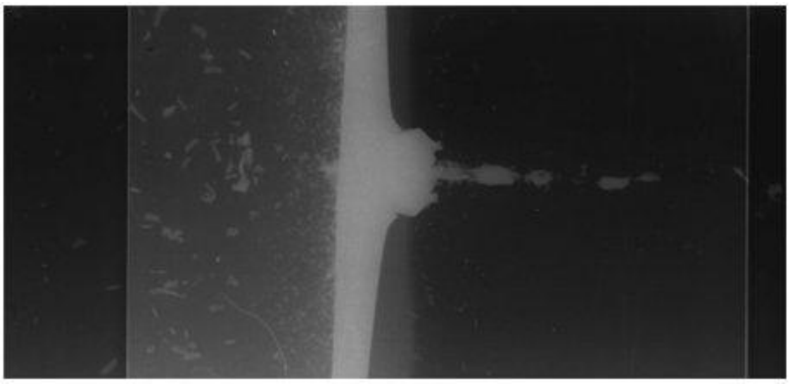

Figure 4.11: Radiography of JC-EFP penetrating medium armour RHA target, 200μs

It is clear from Figure 4.11 that the spall cloud is limited to a few large pieces of armour, as opposed to the larger spall cloud produced by the CSSJ. Further radiography was deployed to observe the JC-EFP at longer stand-offs to obtain a diagnosis as to what was causing the penetration deficiencies in the JC-EFP precursor. The first image shows that a portion of the projectile has been 'pulled away' from the main projectile by the jet portion; which may have affected performance at 45° obliquity.

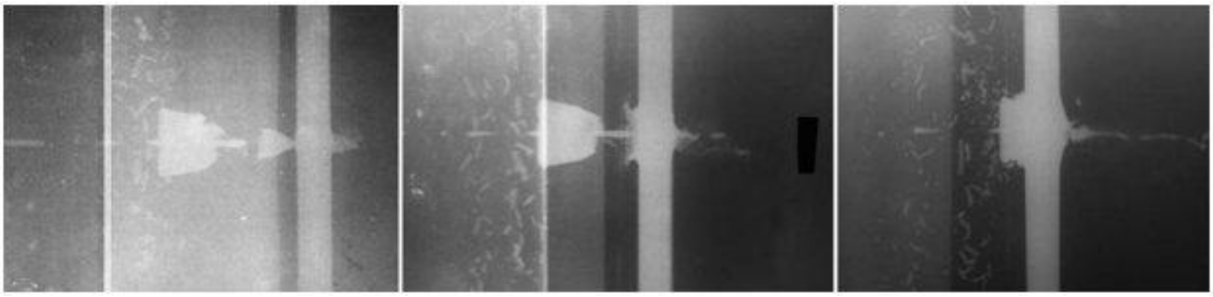

Figure 4.12: Radiography of JC-EFP penetrating the medium armour RHA plate, (left to right) 161μs, 181μs, and 221μs

The results of the JC-EFP firings against the armour target were poor. It was expected that the JC-EFP would struggle to perforate the target at 45° obliquity at a stand-off distance of 1CD. However perforation was restricted to the central jetting portion. Analysis of a firing performed at a longer stand-off provided some explanation. Figure 4.12 shows the JC-EFP perforating the medium armour target, where it is clear at 161μs that the jetting portion of the projectile has caused fracture in the main projectile, demonstrating that the large velocity gradient along the length of the projectile (which was a feature incorporated to defeat concrete) has caused significant instability. It is believed that this design feature has weakened the projectiles ability to penetrate armour targets. A previous variant of the warhead design that did not incorporate the central jetting portion, was able to defeat the RHA target at 45°.

The second trial was performed with the CSSJ warhead only as it was deemed that the JC-EFP would not be effective against thicker armoured targets. This trial focussed on elements of heavy armoured targets, with one firing against the simple armour target as the supply of this armour and warheads was very limited. Previous experiments with the SSJ warhead for the Ministry of Defence had shown that the projectile would penetrate deeper into armour targets at stand-offs greater than 1CD, up to stand-offs as great as 50CDs. Therefore a stand-off which was representative of a crush fuzed system was adopted for this trial, the medium armour firings had been undertaken at 1CD stand-off as this was also thought to be representative of the most effective stand-off for the anti-structures work, therefore providing a common stand-off for two target types.

The CSSJ warhead was fired into an RHA target twice the thickness of the medium armour target to represent some areas of typical MBT targets and also the base armour of older MBTs such as T-55. The armour target was reclined at an obliquity of 45° to provide a greater path length of RHA. The warhead perforated the target, providing a through hole of 0.35CD as shown in Figure 4.13.

Figure 4.13: Damage sustained by MBT RHA plate at 45° obliquity

Following the firing against the simple armour target firings were performed against two ERA configurations, representative of typical protection for MBTs. Both targets were attacked at a 45° dive angle to simulate the typical dive angle for Javelin at a stand-off of 2CD. Figure 4.14 shows the set-up for the first firing. The front plate, overmatch, and explosive layers were instrumented to record impact and detonation.

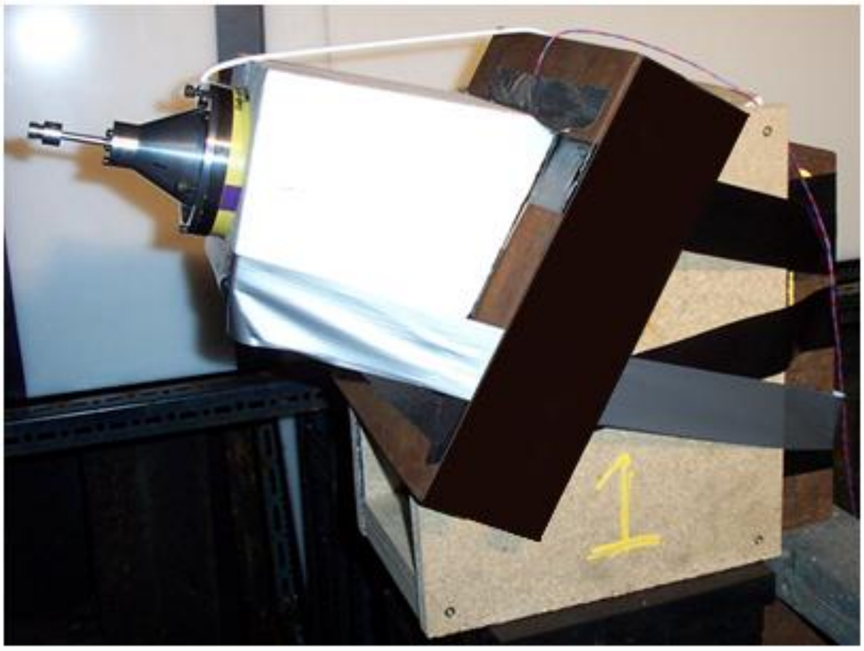

Figure 4.14: CSSJ precursor attacking the MBT ERA target 1

The CSSJ successfully defeated the target but produced no penetration in the overmatch plate positioned to the rear of the target. The CSSJ caused the explosive element of the target to detonate as evidenced from the patterns embossed on the large RHA plates. One of the thicker target elements was split in two, although this is thought to have happened through interaction with the bomb chamber post firing. The penetrator created a large hole through the target. From analysis of the target it is apparent that the heavy plate at the rear of the target was penetrated before being broken in two.

The CSSJ was also fired into ERA target 2 at 2CD stand-off. The target set-up can be seen in Figure 4.15, a dive angle of 45° being applied when firing into this target.

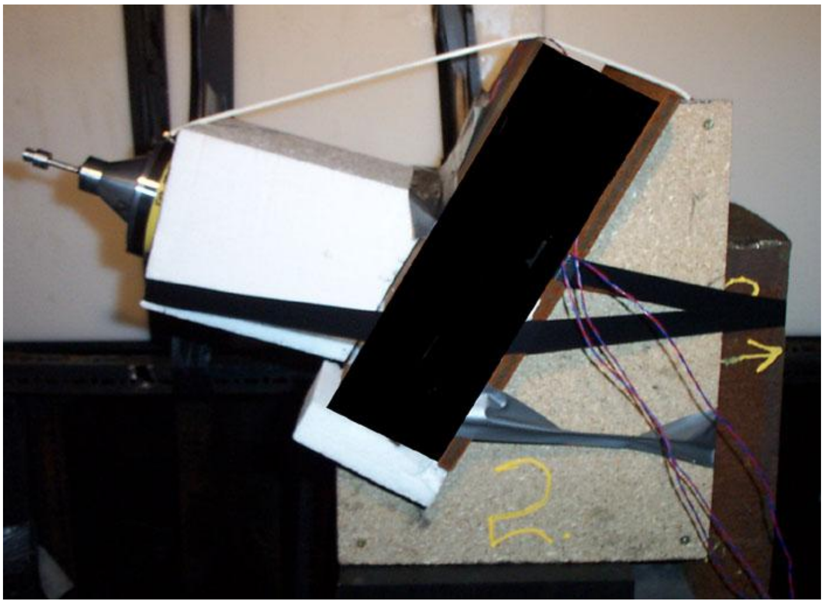

Figure 4.15: CSSJ warhead attacking the MBT ERA target 2

A longer stand-off was required when engaging the ERA targets as it was clear from radiographs that the CSSJ projectile would not have achieved sufficient length to defeat the target. This approach has a clear implication for fuzing; to achieve such a stand-off a sensitive fuzing element would be required. Any crush fuze (such as the one used in Brimstone) must be mounted in a position which would allow a 2CD stand-off to be achieved. An intelligent fuze would be required to ensure that the correct fuzing delay is used for medium armour / structural targets and heavy armour targets.

The CSSJ defeated the target. The CSSJ caused the explosive element of the target to detonate, as evidenced the shear patterns on the large RHA plates that were in close proximity to the explosive. An ionisation probe, which was in close proximity to the explosive within the target, produced a signal that gave a time confirming explosive detonation within a relevant timescale. The projectile created a large hole through the target, it was clear that the rear of the target was significantly damaged from interaction with the explosive in the target, the projectile, and the overmatch plate.

The CSSJ and JC-EFP warheads were also trialled against the structural targets. Because of the results from the anti-armour trial, the JC-EFP was only fired into the reinforced concrete panel target, at 90° and 45°. The trial requirement was to produce through holes in the targets sufficient to allow the Javelin FTB/MC and the Brimstone FTB/MC (with each FTB/MC being different in diameter and length) to pass into the target without any target wall interaction. The set-up for the trials can be seen in Figures 4.16 and 4.17.

Figure 4.16: CSSJ warhead at 1CD stand-off / 90° obliquity (left) 3CD stand-off / 90° obliquity (middle) and sandbag fortification to the rear of the Fortified urban target

Figure 4.17: CSSJ warhead at 1CD stand-off / 45° obliquity (left) 3CD stand-off / 45° obliquity (middle) and front view of the 3m x 3m Municipal target

The CSSJ was fired into the fortified urban brick wall target (which is considered to be tougher than the reinforced concrete panel target due to the sand bag reinforcement) at 90° and 45° obliquities. The warhead perforated the target in each instance, giving a through hole. The damage sustained by the targets can be seen in Figure 4.18, the results for all of the firings can be seen combined with the anti-armour firings in Table 4.2.

Figure 4.18: CSSJ firings against Fortified urban target, (left to right) 1CD at 90°, 3CD at 90°, 1CD at 45° and 3CD at 45°

The CSSJ was fired at the municipal target, at obliquities of 90° and 45° and stand-offs of 1CD and 3CD. The results of the firings can be seen in Figure 4.19.

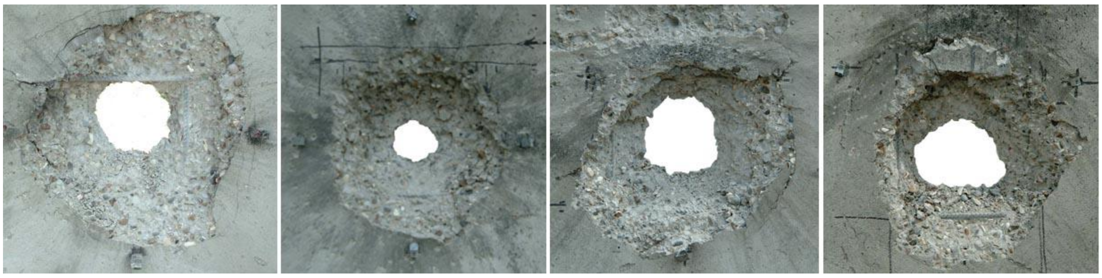

Figure 4.19: CSSJ firings against Municipal target, (left to right) 1CD at 90°, 3CD at 90°, 1CD at 45° and 3CD at 45°

The CSSJ was also fired at the crossing points of the reinforcing bars in the municipal target. As can be seen in Figure 4.20, the first reinforcing bars were cut. However, the projectile did not cut the second layer of bars, although they were bent outwards and gouged due to a glancing impact from the CSSJ projectile. The gouged reinforcing bars are circled in red.

Figure 4.20: CSSJ firing against reinforcing bars of Municipal target, 1CD at 90°

The JC-EFP warhead design was also fired at the municipal target. The images in Figure 4.21 show that the JC-EFP produced smaller holes in the target than the CSSJ.

Figure 4.21: JC-EFP firings against Municipal target, (left to right) 1CD at 90°, 1CD at 45°, 3CD at 45° and 3CD at 90°

The CSSJ warhead produced holes through the targets at both of the stand-offs and obliquities. At 1CD stand-off the precursor warhead produced a through hole that would offer little or no resistance to an FTB/MC of suitable diameter. At 3CD stand-off the holes produced were smaller, but once again the FTB/MC would suffer little trauma from target interaction given a case with sufficient strength, the distance to travel through the target and its weakened state.

The JC-EFP did not perform well. Whilst the central jet portion allowed perforation of the target, it is clear that the performance of the main part of the EFP was adversely affected by this. The trial results are given in Table 4.2.

Warhead Type	Target	Stand-off (CD)	Obliquity (°)	Hole Diameter (% of Baseline)
Baseline	Municipal	1	90	100
			45	100
	Fortified urban	1	90	100
			45	100
	Medium armour	1	90	100
			45	100
CSSJ	Municipal	1	90	90
			45	68
		3	90	55
			45	72
	Fortified urban	1	90	93
			45	42
		3	90	40
			45	53
	Medium armour	1	90	90
			45	90
		3	90	90
			45	90
JC-EFP	Municipal	1	90	20
			45	16
		3	90	30
			45	20
	Medium armour	1	90	154
			45	39
		3	90	Not tested
			45	Not tested

Table 4.2: Anti-Structures and Anti-Armour trials results

Following the anti-structures trial, the JC-EFP warhead design was no longer pursued. The CSSJ warhead did not produce through holes in the target which were large enough for the proposed FTB/MC warhead to pass through without target interaction. However it did produce a path through the targets that the FTB/MC would be capable of passing through without sustaining significant damage. In the worst case, when fired against the fortified urban target, the through hole at 90° was 40% of the baseline performance at a 3CD stand-off. This result was thought to not exclude defeat of the target (FTB/MC entry into a target structure), since the strength of the FTB/MC was considered sufficient to survive interaction with the brick structure. However it is considered that this stand-off would not be used in this application. Following detonation of the precursor, the mortar lines surrounding the damaged bricks were cracked, thereby allowing the FTB/MC to take advantage of the weaknesses in the damaged area and allowing penetration of the brick portion of the target. However the possibility of the momentum of the FTB/MC being reduced by the sandbags is also significant as kinetic energy would have been lost through target interaction. The next worst result was against the municipal target at 3CD stand-off, a through hole diameter of 55% of the baseline performance was achieved, this hole was sufficient to allow FTB/MC survivability. The CSSJ warhead was selected as the precursor warhead design.

4.2 FTB/MC Anti-Armour Experimentation

The FTB/MCs were manufactured and fired in a static trial against RHA at QinetiQ Pendine. The FTB/MC warhead can be seen in-situ in Figure 4.22.

Figure 4.22: FTB/MC warhead in-situ during trials work

The trial set-up is shown in Figure 4.23. The warhead was fired at various stand-offs to enable comparisons with QinetiQ shaped charge warhead data and also to provide information on the possible performance at the related system stand-offs. Flash radiography was used to capture images of the jet as it stretched, providing vital information on jet geometry and velocity.

Figure 4.23: FTB/MC trial set-up

Following observation of some of the target blocks seen in Figure 4.24, it was apparent that significant jet curvature was being incurred, leading to a reduction in RHA penetration.

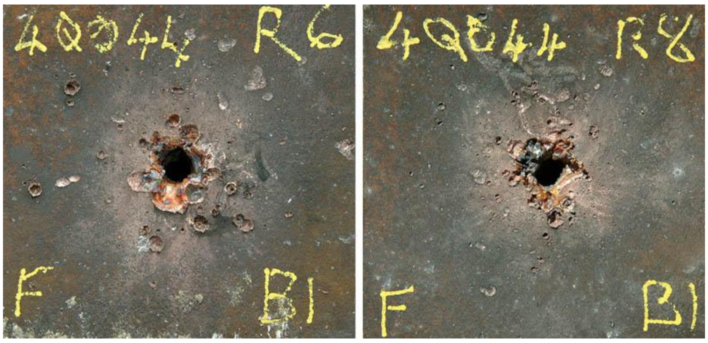

Figure 4.24: Damage to RHA target plates

Figure 4.25 is a graph plotting the entry positions of the jet through the RHA blocks in the target for firing six; each plotted point represents a single RHA block thickness.

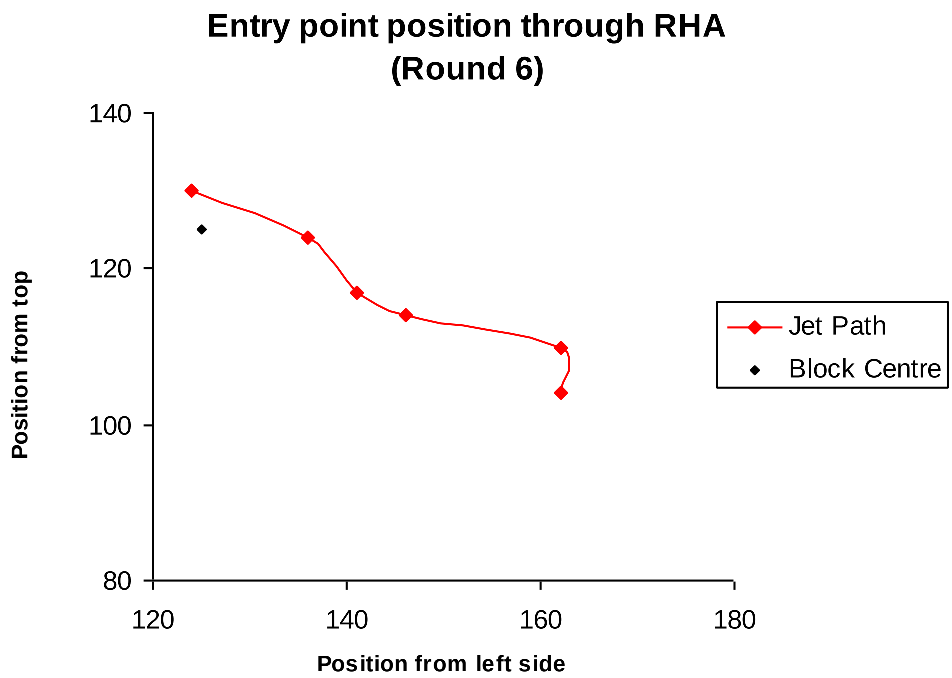

Figure 4.25: Jet path through RHA target blocks

It is well understood that some misalignment can be incurred when building a target, but the pattern exhibited by the entry holes and the keyhole on the front block suggested that there was a substantial amount of curvature along the length of the jet. During set-up, a laser was used to aim the warhead at the centre of the blocks, whilst a calibrated digital inclinometer was used to record the level of the warhead, thereby reducing any human alignment error issues. FXR analysis permitted observation of the jet, and also enabled jet characterisation to be undertaken. The radiographs taken during the trial can be seen in Figure 4.26.

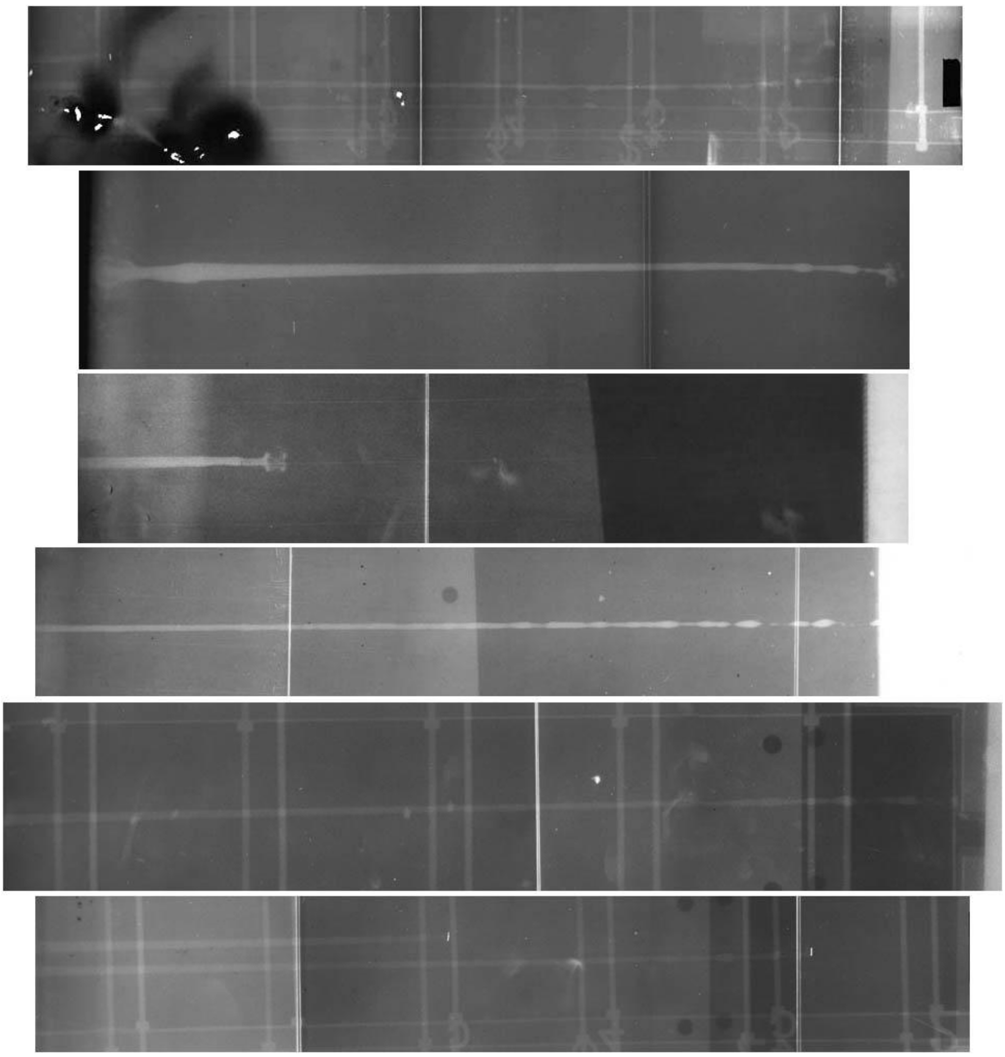

Figure 4.26: Radiography of the FTB/MC, (from top) Firing 1 (140-160μs), 4 (100μs), 5 (70μs), 6 (170μs), 7 (80-140μs) and 8 (90-130μs)

From analysis of the target blocks and the radiography, it is evident that curvature in the jet was present. The extent to which the curvature exists can clearly be seen in most of the radiographs. However, although the radiograph for firing six appears normal, following observation of the target blocks it was obvious that there is significant curvature in the plane in which the radiograph was taken. It is also apparent that the tip of the jet is more perturbed than would normally be the case, which can be related to the initial formation that occurred inside the nose of the warhead. It is possible that gas trapped in the nose of the warhead ('gas guillotine') has caused an early onset of jet particulation. Although this has not occurred to any great extent, it can be seen in Figure 4.27 that the particulation is more advanced in the FTB/MC than in a larger variant of the baseline warhead, the white arrows denoting perturbation within the jet structure. Even though the magnification factors are slightly different, these images serve as a good indicator that the tip of the jet has been affected by the gaseous confinement in the nose of the warhead body and also by penetration of the warhead ogive. These effects become more apparent in the >8CD stand-off regime, whereas the main warhead will normally operate in the <4CD stand-off regime when these effects are not prevalent.

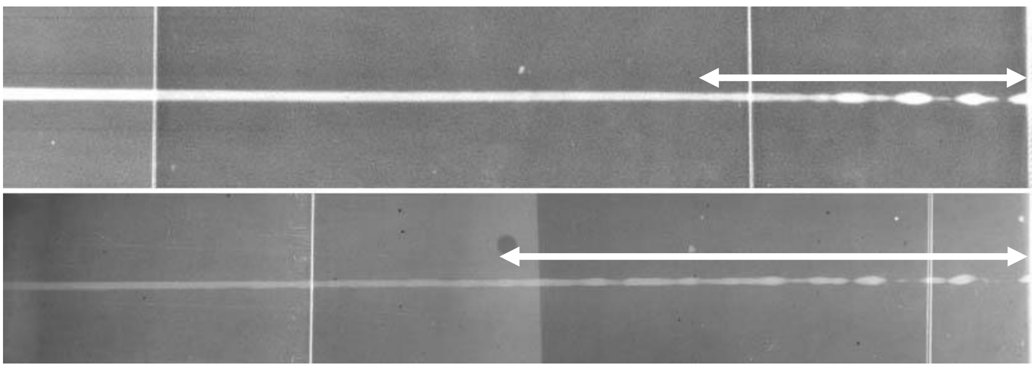

Figure 4.27: Large variant of baseline (top) and FTB/MC (bottom)

The results of the trial are given in Table 4.3. In comparison to the baseline, the penetration performance is reduced. There is a large difference in penetration between FTB/MC and the PBXN-110 filled QinetiQ shaped charge warhead (same calibre for both warhead designs). Jet curvature is the main reason for this performance drop, although the jet tip speed has also been reduced by approximately 5% thereby reducing the available kinetic energy.

Warhead Serial	Stand-off (CD)	Average Penetration Reduction[34]	Notes
1	8	19%	Jet curvature observed on radiography, Jet velocity 0.6mm/μs reduction over baseline
2	4	N/A[35]	
3	4	N/A	
4	5	N/A	Jet curvature observed on radiography
5	5	N/A	Curvature at front of jet, jet tip unusual geometry
6	10	17%	Target key-holed, jet particulation appears advanced
7	8	19%	Jet curvature observed on radiography
8	8	19%	Jet velocity 0.45mm/μs reduction over baseline

Table 4.3: Anti-Armour trials results

[34] Percentage reduction based on like for like comparison against the baseline
[35] No comparisons could be made with 4CD and 5CD stand-offs as the baseline was not fired at those stand-offs

4.3 Summary

This chapter detailed the experimental live trials performed with the MEW warhead system warhead components. Trials were undertaken to observe performance characteristics against various targets, in each case the warheads were trialled singularly. The precursor warhead designs were initially fired against RHA targets, at long and short stand-offs. At short stand-offs they were fired at 90° and 45° obliquities. The CSSJ warhead performed as expected against the targets, however the JC-EFP warhead performance was poor at 45° obliquity. The CSSJ was also trialled against two exemplar ERA targets at representative system stand-offs, it performed well as the targets were disrupted to a sufficient extent.

The precursor warheads were trialled against the structural targets at 90° and 45° obliquities, and at stand-offs that would bracket the Javelin and Brimstone missile systems precursor stand-offs. The CSSJ performed well in these tests, it produced holes through the targets of sufficient diameter to significantly aid emplacement of the FTB/MC. The JC-EFP was only trialled against the concrete target, it did not produce the required hole diameter through the target, it was therefore no longer pursued as a suitable design. The poor performance of the JC-EFP warhead was thought to relate an effect that was observed in radiography. From analysis of the radiographs it was clear that the velocity gradient between the jet and Miznay Schardin portions of the projectile caused significant disruption, thereby reducing the performance of the projectile.

The FTB/MC warhead was trialled against RHA blocks at various stand-offs to obtain an indication of possible performance values. The FTB/MC warhead was trialled at various stand-offs to bracket various possible system stand-offs and provide a basic warhead characterisation.

When trialled against the RHA targets it was clear that the FTB/MC exhibited a reduced performance when compared to the QinetiQ shaped charge warhead design. It was expected that some performance reduction would result from inclusion of the ogive. However following analysis of radiography, it was clear that as well as the 'gas guillotine' effect that the jet suffered from significant curvature. This curvature was apparent when the RHA target blocks were examined, examination revealed significant key-holing which is a key indicator of jet asymmetry, this leads to significant losses in penetration. It was believed that this effect would not be prevalent at the shorter stand-offs which were more representative of current missile systems. It was believed that the jet curvature was a result of processing difficulties related to the use of PBX type explosives, this however was not confirmed.

Chapter 5

Multiple Effect Weapon

System Integration

This chapter will describe how the discreet sub-components discussed in the thesis thus far can be assembled to provide a system which will offer a highly flexible advanced battlefield capability. As some of the component detail is not available for use in unclassified publications, information from patents and public domain sources have been used to provide sufficient detail on possible sub-systems options. An example of how the sub-systems of interest (in block form) would integrate into a missile system can be seen in Figure 5.1. They vary slightly from those in the current missile.

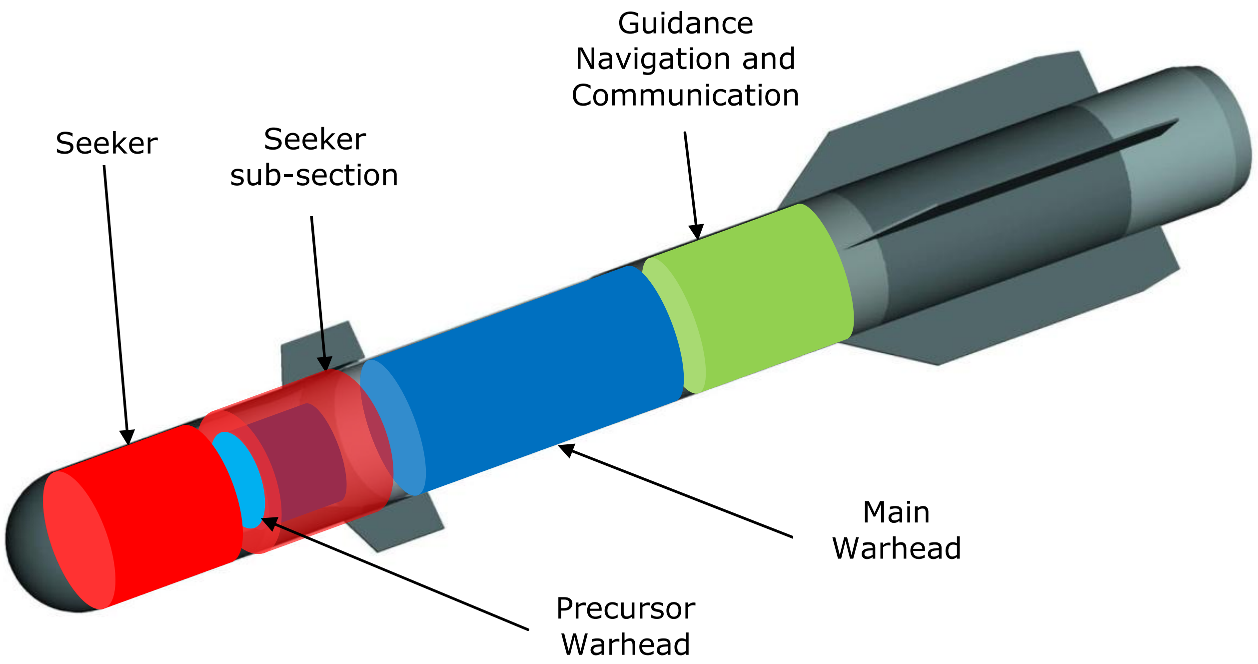

Figure 5.1: Block diagram of possible missile system layout

The example missile system shown in Figure 5.1 is based on the Brimstone missile, which was used to guide the integration process constraints for the current study. Public domain information has been used to support this process, an image which has been used to develop source data is shown in Figure 5.2.

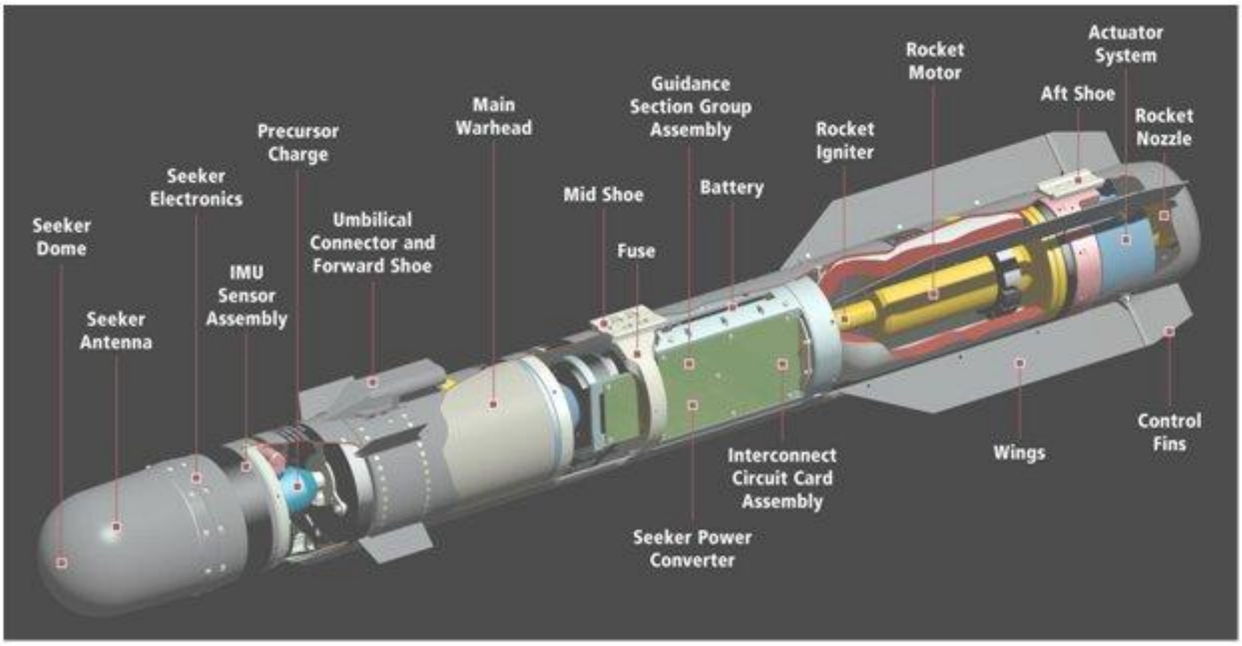

Figure 5.2: Sectioned view of Brimstone missile (image courtesy of Precision Strike Association Annual Programs Review)

5.1 Seeker and Seeker Sub-Section

Several seeker technologies exist; IIR, MMW, SAL, LADAR and SAR have previously been mentioned as appropriate technologies. However these technologies have many attributes which must form the basis for any integration process. A simple SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis can be applied to aid the selection process. Diagrams are shown, Figures 5.3 – 5.7, these illustrate this process.

Strengths	Weaknesses
• Low cost • Well proven technology • Hardened to various countermeasures • Small form factor	• Cooling requirement to ensure good target lock
Opportunities	**Threats**
• Possible use of uncooled detectors • Multi-wave detectors	• Possible spoofing with countermeasures if used as single seeker

Figure 5.3: IIR seeker SWOT

Strengths	Weaknesses
• Hardened to various countermeasures • Suitable form autonomous target detection	• High cost • RF signature makes system vulnerable to DAS
Opportunities	**Threats**
• Aim point optimisation	• Performance may be degraded in high clutter environment

Figure 5.4: MMW seeker SWOT

Strengths	Weaknesses
• Low cost • Well proven technology • Hardened to various countermeasures • Small form factor	• Designator required – line of sight to target
Opportunities	**Threats**
• Small form factor allows integration into multimode seeker	• Use against sophisticated enemy will require off-set designation which could lead to inaccuracy

Figure 5.5: SAL seeker SWOT

Strengths	Weaknesses
• Excellent target recognition • Hardened to various countermeasures	• Highly active – large RF signature • Very expensive • Large form factor
Opportunities	**Threats**
• Target ranging and 3D definition aids aim point optimisation and autonomous target selection	• Use against sophisticated enemy - RF signature will cue defence systems

Figure 5.6: LADAR seeker SWOT

Strengths	Weaknesses
• Well proven technology • Hardened to various countermeasures	• Highly active – large RF signature • Large form factor
Opportunities	**Threats**
• Future developments may lead to decreases in form factor	• Use against sophisticated enemy - RF signature will cue defence systems

Figure 5.7: SAR seeker SWOT

The combination of SAL and IIR provides a good balance in capabilities and technical risk therefore selection of these two technologies is most appropriate for a dual mode seeker system. Brimstone currently employs a MMW seeker, which will also be considered as it is currently integrated with a SAL however it would be preferable to avoid producing any RF signature which would cue any defensive systems.

In the case of the Brimstone missile the seeker section, which is shown in Figure 5.8, also includes the power supply which is situated to the rear of the section.

This element contains a high density of components, which is not ideal for integration with a precursor warhead situated within very close proximity. These components can be repackaged around the precursor warhead, to potentially aid precursor operation and provide an IM benefit by increasing material protection to it.

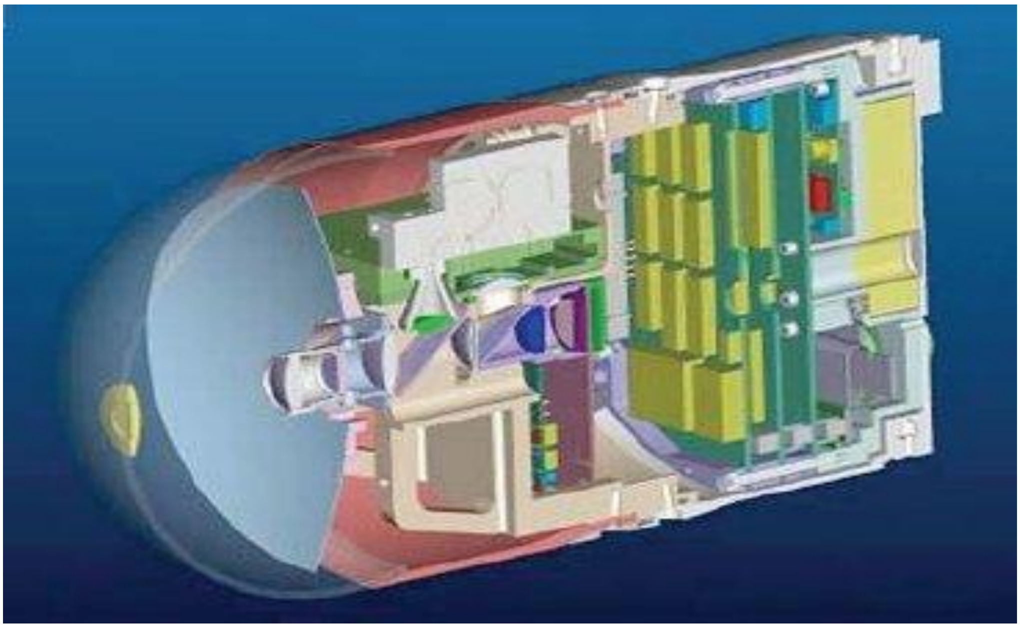

Figure 5.8: Brimstone dual mode seeker (image courtesy of Ministry of Defence)

This seeker technology was retro-fitted to the Brimstone missile fleet following a UOR (Urgent Operational Requirement) which specified a need to reduce collateral damage, as discussed in a presentation provided at Defence Research 2009 [79]. The original MMW seeker was designed to target autonomously, where MBTs were the primary target in a battlefield environment in northern Europe. However the change in use of the weapon - to defeat an asymmetric enemy – required alternative targeting to avoid attacking blue force or civilians, this required the inclusion of a MITL technology, with the best option being SAL. Such a seeker system would be ideal in the attack of a broad target set. The use of the NATO standardised SAL frequencies, specified in the NATO STANAG [80], also allows third parties to remotely designate, with the MMW seeker optimising the terminal dive phase geometry for the best hit point on the target – typically the target centroid. The MMW seeker does not offer the highest level of stealth, although the SAL only mode may be used in this instance. It is believed that currently the SAL mode in Brimstone does not include off-set designation – enabling defeat of laser warners – however this could be included. The re-use of the MMW seeker combined with an integrated SAL offers increased flexibility without the need to carry out a significant development programme.

The current Brimstone precursor warhead is situated to the rear of the seeker. This reflects common practice as the seeker element must have a clear line of sight to the target. However any material on the path of the precursor warhead jet will reduce penetration capability, becoming increasingly significant when obstacles, or 'clutter' are placed close to the front of the warhead. In the case of the current Brimstone precursor warhead produces a thin quickly stretching jet that is not significantly consumed by the clutter. The integration of a larger warhead, which produces a large and slow moving penetrator, into this system provides a significant issue. The close proximity of the rear of the seeker to the front of the precursor will significantly disrupt the penetrator in this case. To avoid this repackaging of the seeker is required with removal of the circuit boards and power supply elements, which can be seen to the right of the seeker in Figure 5.1, to ensure the penetrator is not significantly disrupted. To understand how significant the disruption of the penetrator would be, a series of hydrocode modelling runs were performed. Due to commercial constraints the results from these simulations cannot be presented in this thesis. However the penetrator was severely disrupted, resulting in the single large copper penetrator being fragmented into a number of smaller particles, thereby reducing the potential effectiveness of the precursor warhead. The repackaged elements could surround the CSSJ precursor, using space which is currently unused, as can be seen in Figure 5.2 where the current precursor is surrounded with very few components. This repackaging would also benefit the FTB/MC as its performance is also sensitive to seeker clutter.

5.2 MEW Tandem Warhead System

The MEW Tandem Warhead System comprises of the Precursor warhead and the FTB/MC warhead. To provide some evidence that the FTB/MC would survive detonation of the precursor warhead system further hydrocode modelling was performed. As the FTB/MC required an ogive to enable it to survive entry into structures, it was possible that this design feature could replace the inter-charge barrier that would normally be in place to prevent the main charge from being damaged by the precursor. Such a flat plate inter-charge barrier would also cause difficulties for the FTB/MC when engaging these targets as it would form a barrier to the entry hole in the target and may prevent the FTB/MC from being emplaced inside the target. Hydrocode modelling was used to simulate detonation of the precursor with the FTB/MC at a stand-off representative of the Javelin and Brimstone system constraints. The first and second images seen in Figure 5.9 show the results of unsuccessful designs, with the plots illustrating the blast and fragmentation effect from the detonation of the CSSJ precursor. It is clear that the ogive on the FTB/MC was able to withstand the blast and fragmentation from the precursor as each plot deformation to varying degrees.

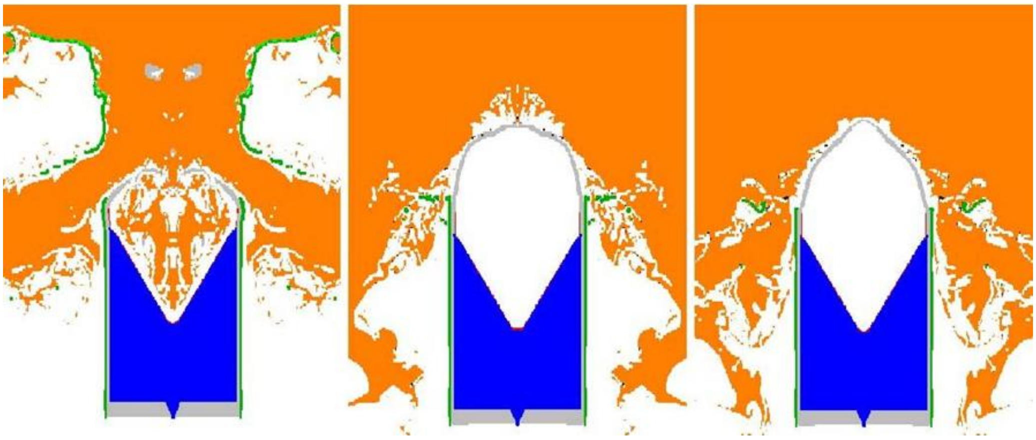

Figure 5.9: Iteration 1 (left) 9 (centre) and 10 (right)

Following significant modelling effort design iteration 10, shown in Figure 5.4, exhibited sufficient integrity to withstand the detonation of the precursor and this design iteration was investigated further. Figure 5.10 shows the final iteration of the ogive design. It is apparent at 400μs that the FTB/MC had survived the detonation of the precursor. The model did not include the proposed seeker sub-section; however inclusion of this sub-system would not significantly alter the results of the modelling, since the components act as a momentum trap as each print circuit board would be crushed and cumulatively lessen the energy deposited into the FTB/MC. Tandem interaction was not investigated in experimental trials as funding would not allow this level of integration to be explored.

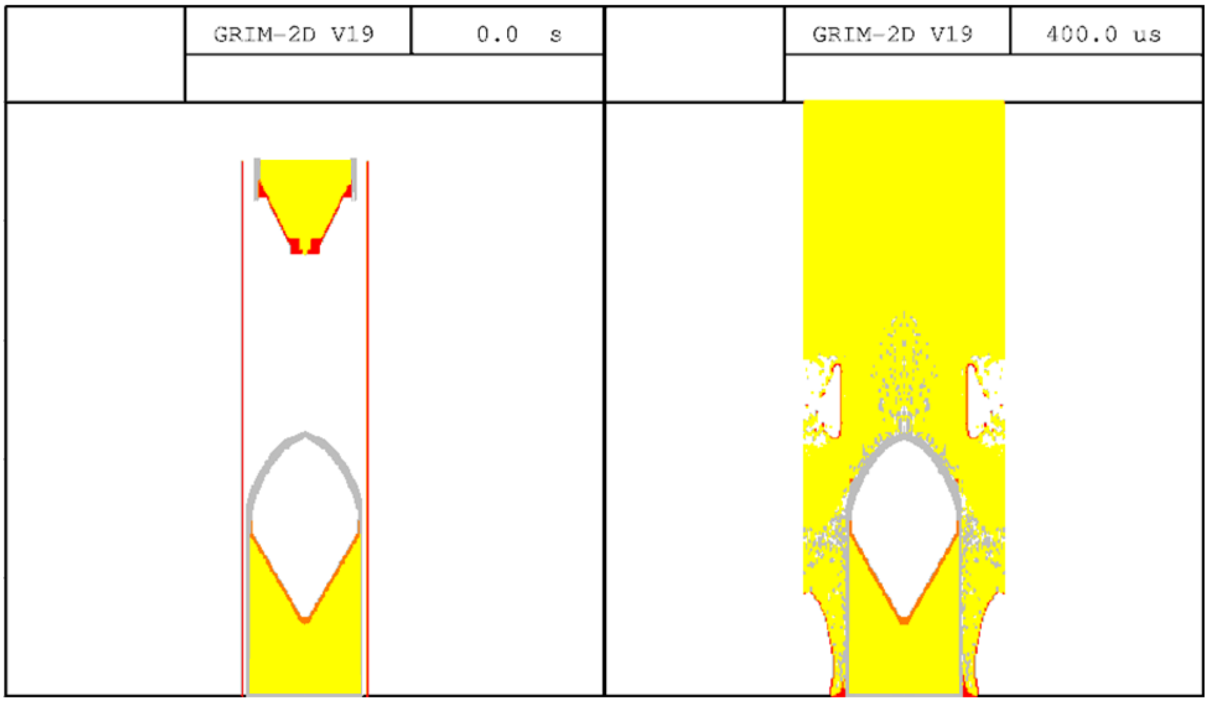

Figure 5.10: FTB/MC surviving detonation of the precursor

As discussed in the paper at the International Symposium on Ballistics presented by Whelan [72], the mass of the FTB/MC would not allow integration within the Javelin missile system. The current Javelin main warhead is encased in a carbon fibre case, used to improve system range. Therefore inclusion of a MEW technology in Javelin would require a smaller warhead than proposed (probably a reduced length to diameter ratio) with a titanium casing. However inclusion of the MEW tandem system in the Brimstone missile is possible, as the mass which can be estimated by using public domain sources [81] for the Hellfire HEAT (High Explosive Anti-Tank) warhead system, which is the same as the Brimstone tandem, is sufficient to allow integration of the warhead system.

5.3 Guidance and Navigation

When missile systems are deployed within visual range of a target the guidance function is typically controlled as a function of feedback from a seeker, using an INS to measure the feedback, or guidance can be supplied through a MITL control system. However when the missile system is required to attack targets beyond visual range or not on the line of sight between shooter and target, additional features which allow autonomous navigation are preferred. An INS can provide guidance to a target area and the seeker can then be used to cue the missile system on to the target. However INS units can drift significantly over long distances.

An integrated INS/GPS provides a good navigation option for a missile system that would be required to travel beyond visual range. This technology has become integrated into missile systems and is starting to be integrated more widely. An example of this is the IGS (Integrated Guidance Systems) product family, manufacturers literature supplied by Integrated Guidance Systems LLC Honeywell / Rockwell Collins [82] which utilizes, what is described as an ultra tightly coupled INS-GPS system for <5m CEP GPS-aided accuracy. The IGS 200 unit also includes anti-jamming which aids guidance and may result in a decreased risk of collateral damage, which is essential when engaging targets in or near urban close combat situations. LCC claim that the IGS products offer good performance against the increasing jamming threat through utilizing inertial sensors to maintain precision accuracy in the event of loss of GPS track, although the exact nature of INS employed is not fully discussed. Details of the IGS 200 INS-GPS unit can be seen in Table 5.1 an illustration of the unit can be seen in Figure 5.11.

Anti-Spoofing	SAASM L1/L2 all-in-view GPS (12-satellite)
Anti-Jamming	>88 dB BB, >95 dB CW (J/S tracking) >59 dB BB, >66 dB CW (J/S D-Y acquisition) Anti-jam 2-channel digital nulling
INS	MEMS digital inertial sensor assembly
Outputs	3D position, velocity, attitude 200, 1200 or 1800 Hz flight control sensing data
Environmental	-43°C to 71°C
Power requirement	<10 W, +5 V input
G-hardening	>15,750 G
Dimensions	Ø71mm x 67mm x Ø83mm (flange)
Mass	0.567kg
Accuracy	<5 m CEP

Table 5.1: IGS-200 product data

Figure 5.11: IGS – 200 INS / GPS unit

The IGS 2XX units are currently employed within various guided weapons in the USA inventory, including weapons such as the GMLRS (Guided Multiple Launch Rocket

System). Such a unit would provide a suitable guidance solution, although the cost of the unit is unknown. The proliferation of the family of INS/GPS units would suggest, however, that an economy of scale exists.

Another candidate for a guidance solution is the AIS (Atlantic Inertial Systems) SiNAV MEMS (Micro Electro Mechanical System) INS/GPS. This unit includes technology which is being applied in the current production run of Excalibur Block 1a1 Ø155mm artillery shell, the AIS SiIMU02 MEMS IMU. The SiIMU02 is a digitally-controlled, 6-degree-of-freedom IMU that has been demonstrated to a g-hardness of over 20,000g in 155 mm live firing trials. The technical specifications of this IMU are well detailed in the paper written by Soheil Habibi et al [83] which details the SiIMU02 IMU capabilities, in particular the MEMS accelerometer is detailed, shown in Figure 5.12.

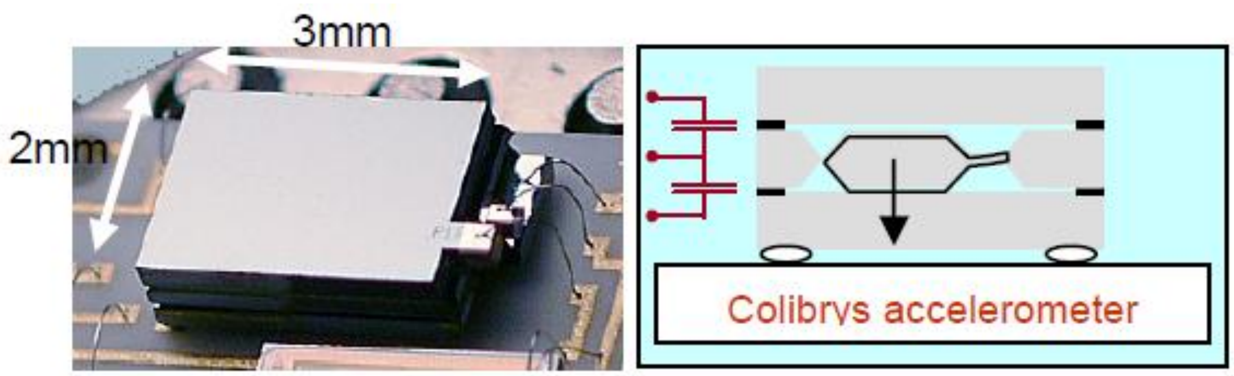

Figure 5.12: MEMS accelerometer and schematic of operating principle

The principle of operation of the accelerometer is differential capacitance with the device based on a mass-spring mechanical system. At zero acceleration the mass is centred between two parallel plates of silicon. The mass moves to one side changing the value of the upper and lower capacitance proportionally to the applied acceleration, which is then translated into data on deviation.

The SiNAV unit, Figure 5.13, demonstrates similar capabilities to the IGS-200 unit with the claimed accuracy of only <10m (with GPS). However there is a reduced power requirement of +5V DC and a reduced system mass of 400g. The size and weight of these units also makes either of them good candidates for guidance solutions for inclusion in the Multiple Effect Weapon, with the final deciding factor being cost, which has not been disclosed in either case.

Figure 5.13: SiNAV INS / GPS unit

Each of the units discussed is capable of receiving new coordinate updates as they incorporate industry standard communication interfaces.

5.4 Communication

Communication with a missile system increases its flexibility, as an asset, or node on a network. Whilst several communication technologies exist the exploitation of current deployed radio systems provides the lowest risk to ensuring that such a system, therefore would be deployable and secure. The most suitable communication system for such a system would be JTRS. As is detailed in a Congressional Research Report on military radio communications [84] the JTRS programme originated in the late-1990s and was intended to replace the 25 to 30 families of radio systems used by the military — many of which could not communicate with each other — with software-defined radios that could operate across the entire radio frequency spectrum. JTRS has moved from being a radio replacement programme into an integrated effort to network multiple weapon systems platforms and combat units.

JTRS is able to operate within LOS (Line-Of-Sight) and BLOS (Beyond Line-Of-Sight) to enhance the C4I (Command, Control, Communications, Computers and Intelligence) capability of mobile and fixed forces. The JTRS programme has developed multiple networking waveforms to accommodate various user applications. This is more fully described in an article written by Chen et al on the JTRS Common Network Services [85]. The paper states that JTRS CNS (Common Network Services) are services that are supported across the JTRS system, across its diverse waveforms, and in support of joint tactical missions. Unlike common network services in commercial LANs that allow multiple clients to share network services on a central Host, the JTRS CNS is capable of supporting services across various physical waveforms, running on different physical platforms. The JTRS CNS is not centralised on one host due to the requirement for ad-hoc mobility of the network, as well as requirement to maintain the reliability demands of a tactical military network. CNS is a solution that provides this common IP convergence layer, as well as network services running at and on top of IP for the hosted networking waveforms in the JTRS family of radios. Bespoke networking waveforms are being developed specifically for

JTRS including WNW, SRW (Soldier Radio Waveform), and JAN-TE (Joint Airborne Network-Tactical Edge). Other waveforms are being included in the Common Library of Waveforms to ensure some interoperability and that legacy waveforms are accommodated, including EPLRS (Enhanced Position Location Reporting System), SINCGARS (Single Channel Ground and Airborne Radio System), LINK-16, HaveQuick and UHF Satcom. The three bespoke waveforms WNW, SRW and JAN-TE serve different purposes:

- WNW uses an adaptive networking architecture that optimises network routing performance and overall network stability for ground vehicular applications. WNW provides wideband OFDM (Orthogonal Frequency Division Multiplexing) and AJ (Anti-Jamming) as the two SiS (Signals-in-Space) to meet different operational needs.
- SRW is optimized for dismounted applications and small form factors. It is designed for small form factors such as man packed radios and sensors that are limited in features. SRW is designed to incorporate networking architectures and protocols that minimise power consumption and software foot print, optimize voice communications and processing requirements.
- JAN-TE is a special purpose networking technology that provides communications for time critical airborne operations. GMSK (Gaussian Minimum Shift Keying) is optimized for achieving the requirements of low latency, enabling high throughput. GMSK was adopted for its tolerance to high Doppler effects caused by fast moving airborne platforms. JAN-TE focuses on providing

communications for the airborne domain that consists of military aircraft including tactical fighters, rotary wing aircrafts and Unmanned Aerial Vehicles.

There are two major considerations that JTRS takes into account to ensure appropriate and secure services; QoS (Quality of Service) and Information Assurance. QoS is a pre-defined network performance level that is offered by the network to the users. The QoS can be measured with pre-determined metrics such as minimum bandwidth, latency, maximum allowable latency variance, and maximum packet loss rate. The JTRS network can carry multiple streams of voice, video and data from users of different priority. The QoS must be able to address the different needs with flexibility. Voice is often treated with the highest priority, although in some cases data may be of a very high priority as it may provide much needed situational awareness data to an infantry platoon which is subject to enemy fire. Unreliable wireless link qualities remain to be the biggest challenge for QoS in any SDR network. The problem is further complicated by the difficulty of sharing the RF channel medium with many users where QoS requirements may vary for each user depending on their roles. To ensure end-to-end QoS cross-layer design between the IP and MANET protocols would have to be implemented. Mapping of IP QoS requirements to time slot reservation in the TDMA network at the MANET layers may allow a reasonable QoS to be achieved in what is essentially an Ad-Hoc network. These considerations are discussed further by Jawhar and Wu in their paper on QoS in Ad-Hoc mobile networks [86].

Information Assurance comprises availability, integrity, authentication, confidentiality, and non-repudiation. JTRS uses an MSLS (Multiple Single Level Security) networking communication system to provide a secure communication environment within the JTRS network. The CNS provides a consistent security architecture including an information assurance solution across all networking waveforms. The JTRS network provides cryptographic system that encrypts the user data to ciphered data, the encrypted data is then carried across the wireless network. The HAIPIS (High Assurance IP Interoperability Specification) developed by the National Security Agency (NSA) is one standard that CNS will support. The HAIPIS is based on commercial IPsec (IP Security), supplemented with remote tunnel endpoint discovery protocol and NSA (National Security Agency) Type 1 encryption. The UK Type 1 crypto code will also be catered for to allow interoperability. While HAIPIS addresses information integrity and confidentiality, the other areas of information assurance are addressed through other CNS such as access control, authentication and secure routing.

JTRS integration into the Brimstone missile is an option which will allow communication with the missile system in flight. There are several other options as previously discussed in Chapter 2, however JTRS will interoperate with the Bowman HCDR as detailed in the Department of the Navy Information Technology Magazine [87]. The article discussed the JBW, which would allow interoperability with Bowman and JTRS radios. The British forces have adopted Bowman as their digital radio system to provide voice and data implying that any future procurement of network or communication system must be compliant with Bowman as interoperability issues within own and coalition forces will become insurmountable. JTRS enables interoperable communications between branches of the U.S. military. The vision of JTRS is to enable networked communications for future forces, while bridging the gap to current operations through legacy waveform interoperability, one of which is the Bowman waveform. The ability to communicate is achieved through the use of a common library of waveforms (radio languages) that all JTRS products will use.

The JTRS radio system is underpinned by an architecture, which provides standardised mechanisms for deployment of waveform applications, the SCA (Software Communications Architecture). The SCA does not mandate a hardware build standard, but it does describe a common approach to configuring and managing a JTRS radio. Typically waveforms are broken down into a number of processing stages and these are deployed on the available hardware resources (with functions being assigned to digital logic in FPGAs or software), a block diagram of this approach is shown, Figure 5.14.

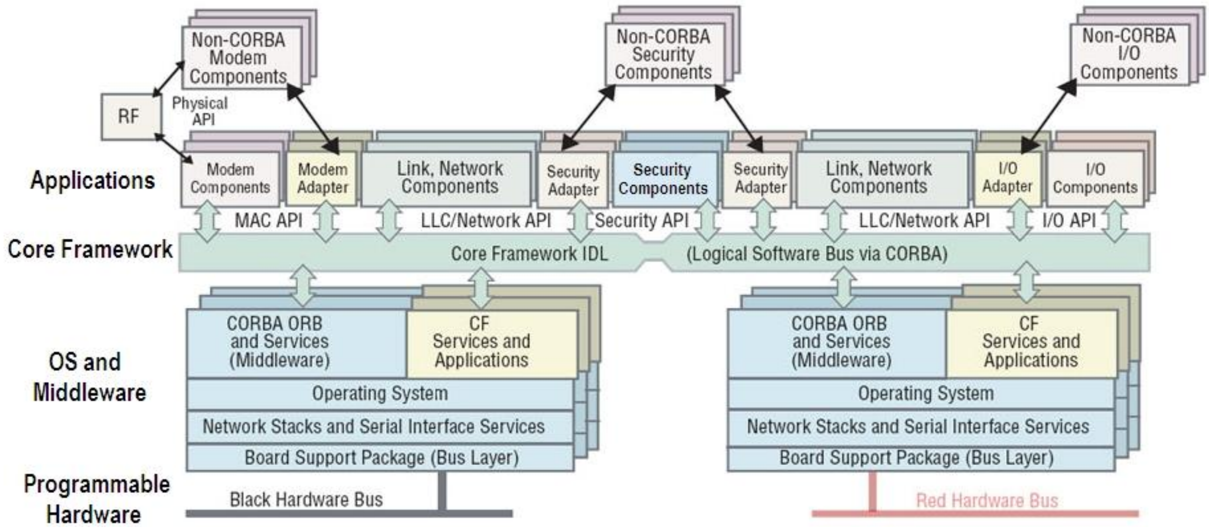

Figure 5.14: Block diagram of JTRS system

The SCA core framework, CORBA middleware and POSIX operating system, provide the major components of the JTRS topology:

- SCA core framework – This is the standardised architecture of JTRS
- CORBA Middleware – CORBA (Common Object Management Request Broker Architecture) is software that allows the waveform / protocol applications running on the radio to be abstracted from the hardware it is

running on. It allows communication to objects within the radio. CORBA may also be used to wrap access to hardware processing elements. The interfaces to the objects are defined in a machine independent manner through an interface definition language.

- POSIX operating system – A real time operating system with a standard POSIX interface for multi-threading and task control is mandated for JTRS.

Application of JTRS SDR to missile systems is enabled through the JTRS SFF (Small Form Fit) radios. Network integration is achieved through the application of miniaturized SDR technology into a family of radios. These radios support systems and platforms such as unattended ground sensors, UAVs, robotic vehicles, weapon systems, and soldier systems. The SSF radio that is most applicable to the application discussed in this thesis is SFF-G, which may be integrated into the PAM NLOS missile system. The SFF-G unit is further discussed in a presentation provided by the JTRS Joint Programme Executive Office [88] and it is also identified in the system overview of JTRS in the Supportability Strategy report for JTRS [89].

The capability of this radio system is discussed in some detail in a report authored by Emis et al for the Naval Postgraduate School [90], written from a naval perspective as the PAM NLOS system was also planned to be integrated into the Littoral Combat Ship. Emis states that pre-launch communications for the PAM missile are performed by a hard-wired Ethernet connection between the Command Launch Unit and command and control. Emis also carried out calculations on the probable range of the NLOS Radio with the assumption that the antenna height of the launch system being at least 100ft. This did not include any third party communications enabler[36], although, the calculations are given in Equation 5.1 and the example results are shown in Table 5.2, using data to support this calculation being provided by Raytheon [91]

$$D = 1.33\ (\sqrt{2 \times Hr} + \sqrt{2 \times Ht})$$

Ht = Height of Antenna (in feet)
Hr = Height of PAM in Flight (in feet)
D = Radio Line-of-Sight (in miles)

Equation 5.1: PAM NLOS JTRS cluster 5 radio range

Ht (feet)	Ht (feet)	Maximum range of the radio (miles)
100	500	61
	1000	78
	1500	92
	2000	103

Table 5.2: Example radio range – PAM NLOS

The results shown in Table 5.1 are relevant to the line-of-sight of the radio from an antenna mounted 100ft from the deck of a DDG-51 class destroyer to an antenna on a PAM in flight. It does, however, give a theoretical indication of what the expected JTRS radio performance would be. Emis points out that the curvature of the earth limits the range of the radio and that due to the receiver sensitivity, transmitter power, and antenna efficiency the actual range of the radio is expected to be lower than the theoretical values. The use of this radio system would provide a suitable communication system for the proposed MEW system.

[36] Third party enablers include systems such as ASTOR or JSTARs platforms which may be at high altitude, thereby affecting communication capability

5.5 Systems Architecture

The combination of these technologies provides a system which contains multiple sub-systems and multiple linkages both internal and external. To more easily understand these linkages and dependencies diagrams, Figures 5.15 and 5.16, illustrate the systems architecture and the systems functional flow. It is assumed that target positive identification has been confirmed in both cases.

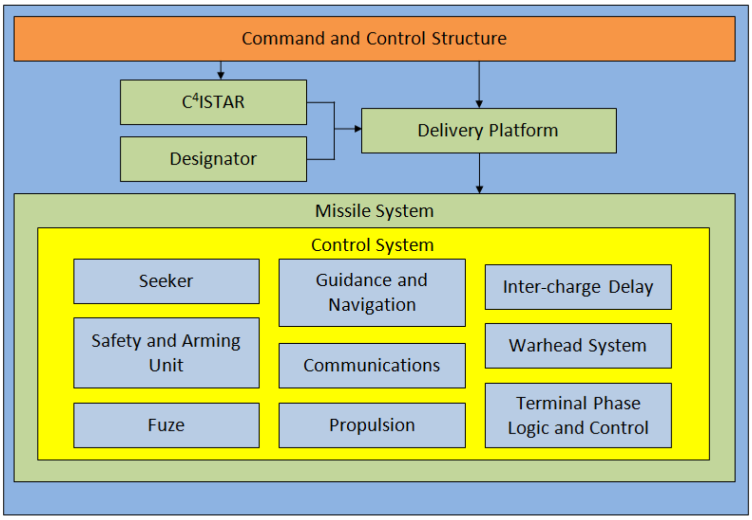

Figure 5.15: Systems Architecture diagram

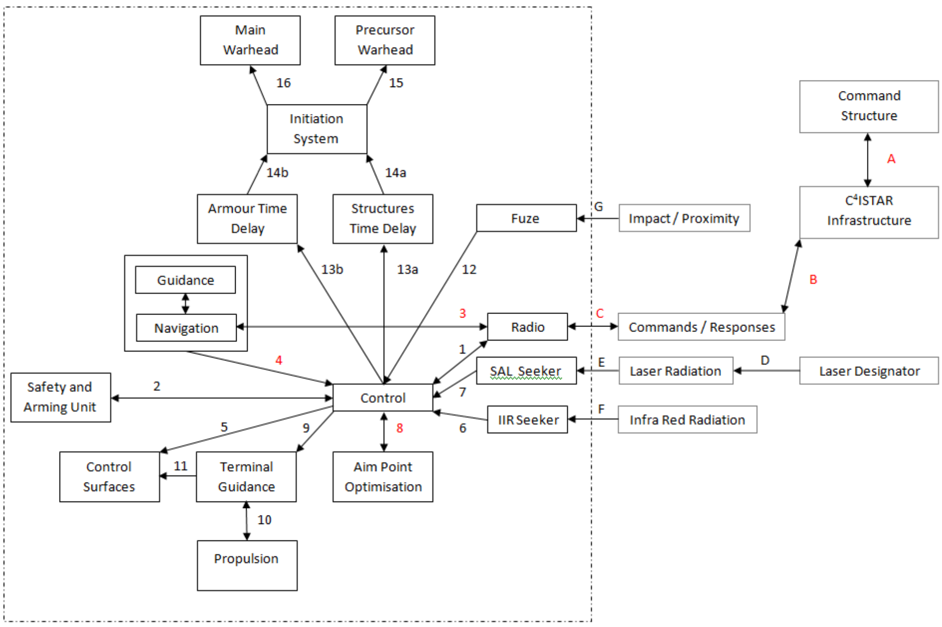

Figure 5.16: System Functional Flow diagram

The diagram shown in Figure 5.16 illustrates the complex nature of the sub-systems linkages and the links to external elements, the missile system is represented by the large dashed outline box. The nature of the linkages can be seen below.

A. The command structures intent is passed to force elements and the Command, Control, Communication, Computing, Intelligence, Surveillance, Targeting, Acquisition, and Reconnaissance assets to execute instructions – this may include the delivery platform.

B. Commands and responses are used to inform and update.

C. Instructions are conveyed to the missile system.

D. The designation system provides a targeting input.

E. The laser reflection provides an aim point to the SAL seeker.

F. Infra Red Radiation signature provides a target profile following SAL designation.

G. Impact or proximity provides an input stimulus to the fuze.

1. The communication system provides constant updates to the control system.
2. The safety and arming unit provides the arming condition for the warhead system via the control system when safe separation conditions are achieved.
3. The guidance and navigation system update and are updated via the communication system.
4. The guidance and navigation system compares current navigation assumptions with required end state.
5. The control system instructs suitable changes to the control surfaces to ensure appropriate flight profile is achieved.
6. The Imaging Infra Red seeker updates the control system.
7. The Semi Active Laser seeker updates the control system.
8. The Aim point optimisation logic provides guidance to the control system on appropriate terminal phase manoeuvres.
9. The control system updates the terminal guidance flight profile logic.

10. The terminal guidance logic instructs the propulsion system to alter its operating conditions to match the required terminal guidance profile.

11. The terminal guidance logic instructs the control surfaces to alter their operating conditions to match the required terminal guidance profile.

12. The fuze provides an input signal indicating that the target is at the appropriate stand-off.

13. Time delay is selected following input from the control system.

14. The appropriate time delay is selected to achieve the appropriate effect on the target and the initiation system responds with a suitable time delay between the two warheads.

15. The precursor warhead is initiated.

16. The main warhead is initiated.

It is clear that system integration 'hot spots' exist in the overall system and system of systems. As shown in Figure 5.16 the 'hot spots' are designated with red characters. The links A,B and C are dependent on secure communication links that provide a suitable QoS. Links 3 and 4 provide guidance feedback information internally and externally, this information is crucial to the guidance of the missile system. Link 8 provides feedback on appropriate terminal manoeuvres that are required to impact the target in an appropriate position, this link will ensure that the required effect is delivered to the most suitable impact point.

Such a sophisticated system of systems and missile system will be subject to several key risks. The communication system provides an essential link, it will carry updates to targeting information and where appropriate it will send commands to terminate the mission. Lack of bandwidth and signal weakness will cause system performance to suffer, to ensure this is mitigated against a suitable communications backbone and radio unit must be selected. Seeker selection depends upon the required operating conditions and the target set. The use of a single seeker can limit the missile to operating within a limited set of conditions. To mitigate this limitation the selection of a suitable dual mode seeker should be made, a seeker arrangement which is well proven in a similar packaging arrangement should be selected. The use of aim point optimisation provides an extra assurance that an appropriate effect is delivered to the target. When a target that is not recognisable to the aim point optimisation logic is engaged some effectiveness against the target may be lost. To mitigate against this the target centroid would be selected as the aim point, this ensures a good probability of impacting a crucial element of the target.

5.6 Summary

The MEW warhead is a result of a combination of technologies which have been integrated to provide effects against the wider target set. The trials demonstrated that the warheads have very good utility against the wider target set. Modelling of the tandem system suggested that survivability of the FTB/MC would be achievable, although jet formation following precursor detonation was not modelled.

Guidance is becoming increasingly important within the military. GPS technology has proliferated quickly with the result being small, low cost, and reliable units. Tightly coupled GPS/INS units are being incorporated into mortars in the PGMM (Precision Guided Mortar Munition) programme and the 155mm Excalibur artillery shell. These units are well proven and the cost has decreased to a level where incorporation into complex weapons such as Hellfire or Brimstone would only marginally increase missile unit cost. Given the proliferation of this technology, integration is seen as being low risk, particularly in the case of the units discussed in this thesis.

The JTRS family of radios will soon provide the communications backbone for the United States armed forces, with the intent of producing a family of radios which will provide network connectivity to all network nodes. Missile systems will soon become another node on the network therefore selection of this technology is the most secure and possibly the most cost effective choice for a communications effector.

The combination of these elements within a missile system such as Hellfire or Brimstone is possible and may become a more widely adopted weapon technology in the next generation of weapon systems.

Chapter 6

Conclusions

6.1 Conclusions

The MEW warhead system discussed in this thesis offers a novel approach to defeating a wide target spectrum. One other approach (JAGM) has considered an FTB/MC but it may lack (data is not available as it is US DoD classified) the anti-structures capability offered by the MEW system. The precursor warhead in JAGM is traditional in design therefore it will only produce a narrow hole through a structural target, this may limit the ability of the FTB/MC to penetrate target walls.

This thesis has considered the use of new MEW warhead technologies and how the integration of such technologies into a missile system equipped with modern communication, seeker and guidance technologies would provide a precision strike capability that would reduce the need to use larger more destructive systems. The use of Military Off-The Shelf technology (Seeker, Radio and Guidance) provides a capability that would lessen the development cost for such a system and it may lessen platform integration costs.

Javelin cannot be considered as a suitable candidate system for the MEW technology as explained in this thesis. The warhead system weight will not be compliant with the system parameters if the main target effect is to not be affected.

It is clear that integration of the sub-systems discussed would require significant design efforts as Centre of Gravity considerations must be taken into account particularly when the manoeuvre of the systems discussed is controlled by relatively small control surfaces.

Such a system will provide a more precise strike capability to commanders, the use of highly precise GPS coupled with INS will deliver this capability.

The use of precision strike weapons has become ever more important to commanders. The integration of communication, guidance and mature seeking technologies has provided an ability to strike at targets whilst reducing the risk of collateral damage.

The infrastructure required to support this approach is not currently in place, further developments in the UK military communications strategy may provide this.

6.2 Recommendations for further work

Tandem integration of the warhead system should be undertaken to understand the strength of design.

Future work should seek to exploit design information on suitable missile systems. Some of this work has been investigated by QinetiQ in cooperation with major defence partners. Adopting a family of systems may reduce platform integration costs.

Future work should exploit opportunities offered by the improvements in digital electronics. The use of FPGA technology is an example of this. Improvements in resolution of IIR seekers should also be exploited to improve target identification at long ranges. The use of SDR provides a capability that will convert many more elements on the battlefield into a node on the network. To support this the UK NEC strategy must encompass this approach and solve the inevitable information over-load that will result.

Fuzing has not been discussed in any detail in this thesis as it is the subject of other research programmes within the Ministry of Defence. This is another key technology that is required to enable the proposed system to work. Integration of a 'Smart' fuze which considers inputs from the SDR and is able to change inter-charge delay is crucial to the successful development of such a system. Such fuzing technology is in service, in particular they are used in the attack of deeply buried targets, some idea of how such fuzing systems work is given by Foley et al at the 52nd NDIA (National Defense Industrial Association) Fuze Conference when he discusses the MAFIA (Modular Advanced Fuze Interface Architecture) [92]. Such fuzes can greatly improve the utility of a missile system even when the warhead design has not been optimised in to attack various target types, it is recommended that future research into this field includes integration of a ‘Smart’ fuzing system.

The inclusion of subsystems which reduce collateral damage and increase weapon system utility must be pursued as a matter of priority.

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