

BEng (Hons.) Ordnance, Munitions and Explosives (Test & Evaluation Pathway)

ACDA 6008 – Level 6 Scientific Principles of OME Design: The theory and application of fuel-air explosions

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Abstract

The following report summarises the mechanisms of explosives, involving details of combustion, deflagration, detonation, and deflagration to detonation transition. How these processes are used in both conventional explosives and Fuel-Air Explosives (FAEs). It shows how although FAEs present a much lower pressure and velocity of detonation they far exceed conventional explosives such as TNT in power due to a high heat of detonation (combustion). This coupled with their flexibility to present a distributed detonation makes them ideal for defeat of many military targets including personnel (both in the open and in cover), buildings, armoured vehicles, and armour dependent on ingress of dispersed fuel, grounded aircraft and counter-mobility obstacles such as mine fields. In short FAEs offer a good variable and flexible return on investment.

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1. Introduction and method

The aim of this report is to explain the theory behind the phenomena of fuel-air explosions (FAE) and identify possible targets within the military environment which could be defeated by such means. This report aims to investigate possible effects of FAE on a number of different types of target, such as armour, structures, personnel, counter-mobility obstacles and aircraft. On the basis of this investigation a suggestion will be made as to which of the aforementioned target types would be best suited to defeat by FAE. Considerations will include the mechanism by which FAE are propagated and their resulting blast waves in air, these will be compared to conventional explosives such as TNT and RDX. [1]

2. Method

This report will utilise a number of different techniques to ascertain the information required, including, but not limited to the following: literature reviews, case studies, use of diagrammatic and graphical data representation and analysis to enable comparison of attributes or different explosive types.

Research will be carried out to determine the theory behind both FAE and conventional explosive initiation and affect mechanisms.

3. Fundamentals

3.1. Combustion

To be able to compare the effect of any type of explosive firstly the mechanism of initiation and propagation must be found and definition of an explosive must be ascertained.

An explosive reaction is not simply combustion, as combustion is a process whereby a fuel is ignited by a heat source in the presence of oxygen to produce solid and gaseous products over time.

Explosive reactions typically fit into two main categories deflagrating and detonating, both of these types of reaction are a type of combustion as they require fuel, an oxidiser or provider of oxygen and heat, whether by way of an electrical spark or impulse, friction, impact or direct heat such as flame. [2]

3.1. Deflagration

An example of deflagration can be seen below in figure 1. Note that the propellant burns layer by layer, as the first layer burns the layers below then vary in temperature and pressure as the gaseous products back fill the space building the pressure behind (above) the burning front and effectively pushing it forward (or downward) this in turn effects the concentration of the gas products produced from the regressing surface. Deflagration continues due to thermal transference by means of conduction in the media, convection within hot gases and Infra-red (IR) radiation, which all contribute to the required stimulus and Activation Energy (AE) required to continue the compositional breakdown of the reactants to chemically form the deflagration products. [2] [3]

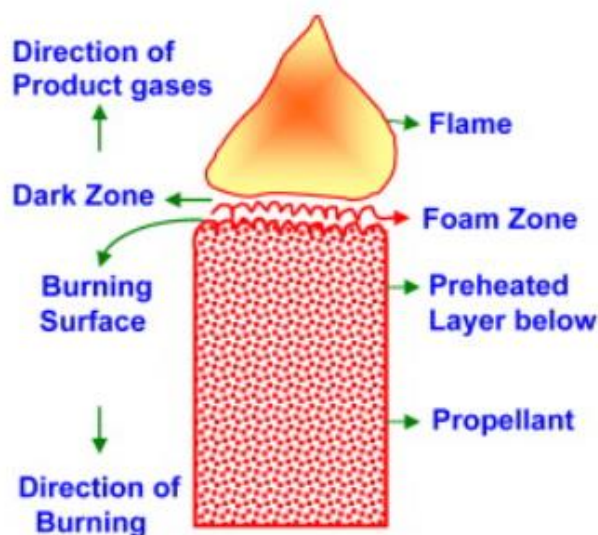


Figure 1: Deflagration of a propellant stick [3]

However, the key identifying characteristic of deflagration is the burn rate. The burn rate of any deflagrating or low explosive is said to be sub-sonic for the media or below the speed of sound for the explosive. Examples of which would typically be pyrotechnics and gun powder. [2]

3.2. Detonation

Detonation produces a shockwave in the material that is notably faster than the burn rate in a deflagrating explosive and is said to be supersonic or faster than the speed of sound within the media. Associated with the high speed shockwave is a high temperature and pressure, this wave causes instantaneous decomposition of the explosive reactants in the media within the chemical reaction zone as seen in Figure 2 below.

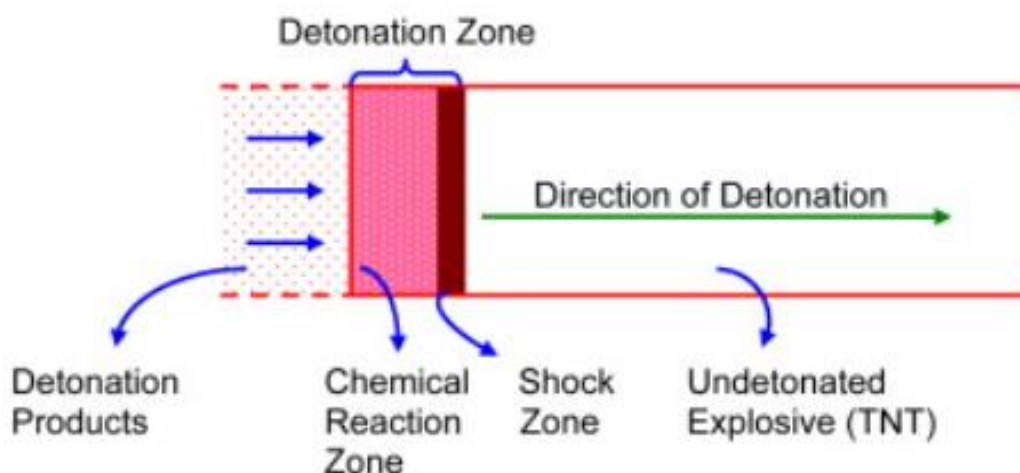


Figure 2: Detonation of an explosive [3]

Unlike in a deflagration reaction, the gaseous products in a detonation reaction flow in the same direction as the direction of the detonation wave. Meaning that a lot of heat and pressure are produced in a very minor time frame. The rate of detonation wave transmission and therefore movement of the detonation front is known as the velocity of detonation (VOD) [3]. It should be noted that if confinement is high enough and pressure from the gaseous product production accelerates the burning front in a deflagrating explosive it can cause it to detonate in a Deflagration to Detonation Transition (DDT) [2]. Below in figure 3 are some examples of different VOD for both Primary and Secondary explosives.

Explosive	Density/g cm ⁻³	Detonation velocity/m s ⁻¹
<i>Primary explosives</i>		
Lead styphnate	2.9	5200
Lead azide	3.8	4500
Mercury fulminate	3.3	4480
<i>Secondary explosives</i>		
HMX	1.89	9110
RDX	1.70	8440
PETN	1.60	7920
Picric acid	1.60	7900
Nitroguanidine	1.55	7650
TATB	1.88	7760
Nitroglycerine	1.60	7750
Nitrocellulose (dry)	1.15	7300
Tetryl	1.55	7080
HNS	1.70	7000
TNT	1.55	6850

Figure 3: Detonation velocity of Primary and Secondary explosives [4]

3.1. Real world effects

The main desired effects of an explosive are to defeat targets, the graph below shows how the detonation wave and VOD give rise to a massive peak pressure typically measured in Giga Pascal i.e. billions of Newtons of force per square meter. This amount of pressure subsides over time and then forms a negative pressure. The positive pressure integrated with respect to time gives the blue area in the graph below in Figure 4, which is equal to the impulse of the explosive or work done by the explosive [5].

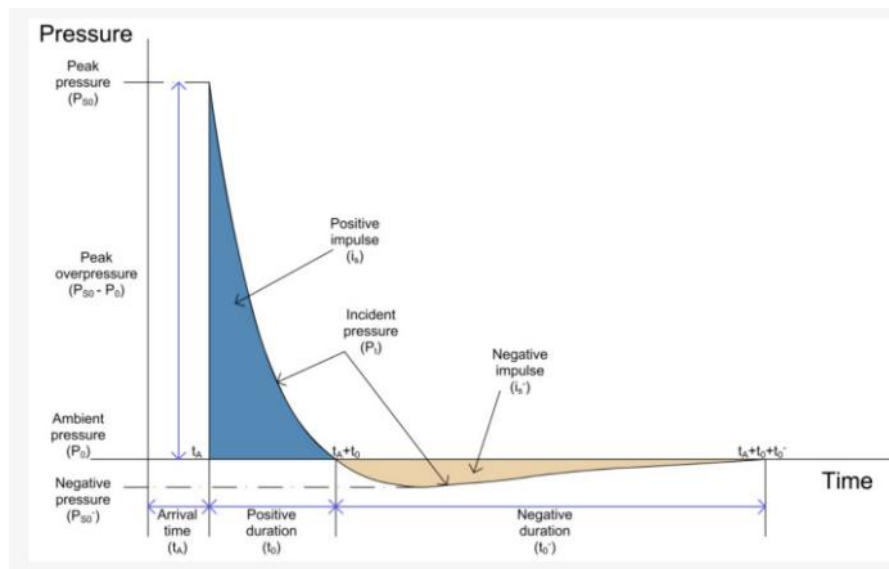


Figure 5: Ideal blast wave pressure vs time graph [5]

It should be noted however that the beige area of negative pressure also does work, in that a partial vacuum effect is caused and causes objects and people to be sucked out of building/ cover if not properly secured. The effects of such blast can be seen in figure 6 below [6].

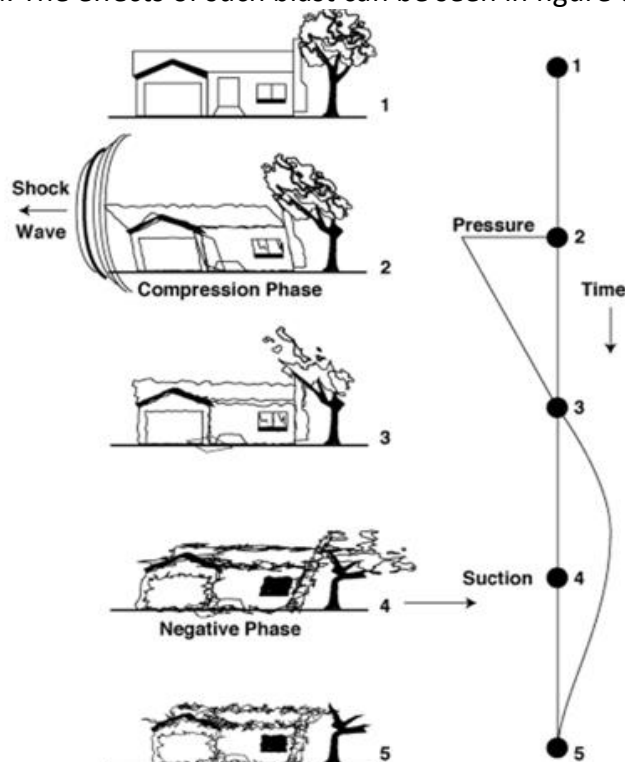


Figure 6: Destructive effects of blast [6]

All of the above is a summary of how an explosive works and how it generates its' effect on its' target. The rest of the report will look at how Fuel-Air Explosives (FAEs) differ from conventional explosives and how they have been used in the past.

4. Fuel Air Explosions mechanism and a brief history

Fuel-Air Explosives (FAEs) are a sub class of volumetric weapons, which also include thermobaric weapons and these terms are often used interchangeably [7]. Unlike a conventional molecular explosive that contains it's own oxygen within, FAEs rely on atmospheric oxygen. In general, a fuel is dispersed as an aerosol of gas, liquid or gel and is detonated using the atmospheric oxygen to feed the explosion. Examples of this type of premise can be seen as far back as the Second World War (WWII) in which the German Army utilised a six barrelled Nebelwerfer rocket launcher on the Eastern Front. This weapon consisted of 6 rounds, the first 5 rounds were used to distribute the fuel over a large area and the sixth round detonated it. The United States (US) started using FAEs in the Vietnam War, as did the Soviet Union during their war in Afghanistan and the Russians in Chechnya. [8]. Many of these devices utilise conventional explosives to disperse the fuel and a secondary charge to detonate it.

It is now possible not only to have air drop weapons which can deliver this capability as seen in figure 7 (below) the delivery, dispersion of fuel and detonative effects can be seen. There are also man portable systems including Rocket Propelled Grenades (RPGs) and a 42mm magazine fed grenade launcher and field artillery shells [8].

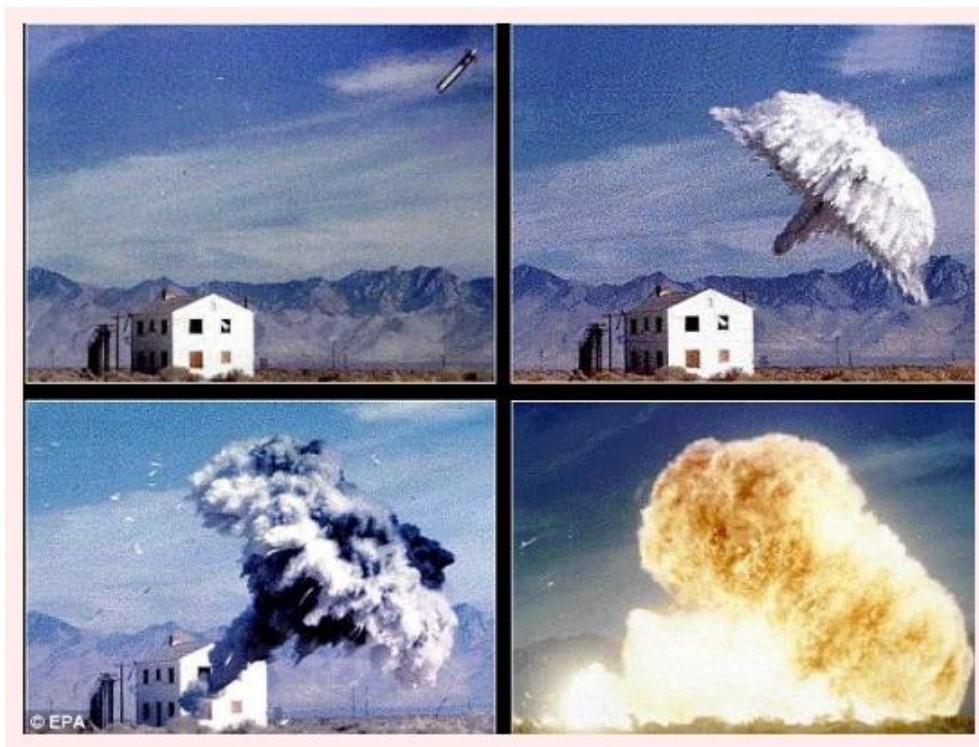


Figure 7: The three stages of FAE use [9]

An FAE consists of a fuel and a source of ignition, when combined with air generates a large amount of heat and pressure, for example the heat of combustion of a typical fuel such as ethylene oxide can be six times that of TNT, with a specific volume 800 times that of TNT [10]

Fuel	Explosive limits by vol. (%)	Auto ignition temp (°K)	C.J. detonation parameters			Reported pressures (1) inside the detonation zone (MPa)
			Pressures (MPa)	Velocity (m/s)	Temp. (°K)	
Methane	5-15	713	1.742	1802	2784	2.3
Acetylene	2.5-100	578	1.939	1864	3114	-
Ethylene oxide	3-100	702	1.963	1831	2949	3.2
Propylene oxide	3-27.5	738	1.980	1826	2930	1.8
n-Heptane	1-7.0	595	1.889	1800	2828	
Heptane + 10% n.propylnitrate	-		1.902	1803	2835	
Heptane + 20% n.propylnitrate			1.917	1806	2843	

Figure 10: Detonation parameters for stoichiometric fuel- air explosives [10]

For TNT (from Figure 3) the VOD is 6850ms^{-1} which is much larger than say Ethylene oxide with a VOD of 1831ms^{-1} . However due to the relatively long time of explosion in comparison to TNT and much higher heat of detonation the FAE provides a much greater power. Other than stoichiometry (the ideal fuel to air ratio for maximum combustion) other factors affect the maximum power delivery from an FAE, these include:

- **Droplet size of fuel** – The greater the droplet size the greater the amount of charge required to initiate the fuel
- **Chemical behaviour of the fuel** – sensitivity data of different fuels has shown that the lower the bond energy of the fuel the more prone the fuel is to detonation
- **Effect of additives** – It has also been shown that the addition of additives such as nitrous oxide can reduce ignition delays in fuels [6] [10].

5. Effects and uses

Knowing that FAEs can be used to produce a power much greater than conventional explosives such as TNT and produce a much higher heat on detonation, how can they be used on military targets. Looking into the different types of military target will give an insight to possible uses.

5.1. Military target types

Infantry and structure – Figure 11 below shows that at nearly 2MPa of pressure FAEs would be capable of severe injury and death, especially as they are capable of causing a vacuum effect, which sucks people out from cover as well as debris and causing death by destruction of covering building [11].

Peak Over-pressure	Max. Wind Speed	Effect on Structures	Effect on the Human Body
6.9 kPa (1 psi)	61 kph (38 mph)	Window glass shatters.	Light injuries from fragments occur.
13.8 kPa (2 psi)	113 kph (70 mph)	Moderate damage to houses occurs (windows & doors blown out, severe roof damage).	People are injured by flying glass and debris.
20.7 kPa (3 psi)	164 kph (102 mph)	Residential structures collapse.	Serious injuries are common, fatalities may occur.
34.5 kPa (5 psi)	262 kph (163 mph)	Most bldgs collapse.	Injuries are universal, fatalities are widespread.
68.9 kPa (10 psi)	473 kph (294 mph)	Reinforced concrete bldgs are severely damaged or demolished.	Most people are killed.
137.9 kPa (20 psi)	807 kph (502 mph)	Heavily built concrete bldgs are severely damaged or demolished.	Fatalities approach 100%.

Figure 11: Explosion peak over-pressure effect on structures and the human body [11]

There are specific injury types, which are more likely expected to be received by humans experiencing FAEs, these include pressure damage to the lungs resulting in pneumo/haemothorax, bursting of the ear drums, affects to the heart and head and many more systems as shown in the Appendix [8].

Armour – Armour is not as easily defeated, however if the fuel delivery system can get into the engine bay of armoured vehicles and between armour plates before detonation it can be wholly more effective in rendering the capability useless

Aircraft – The problem with use on aircraft is that if used at altitude the oxygen concentration is lower, meaning that the power of an FAE may be less effective. Coupled with the fact that because there is less air, there is less dense media to propagate the shockwave, so the FAE would have to be much larger to generate the same effect as at a much lower altitude [6]. That being said an FAE would be perfectly viable against grounded aircraft and would be able to move around obstacles such as embankments and still

detonate effectively to destroy the target, where a conventional explosive blast would be mostly mitigated by the embankment around the aircraft if not struck directly or directly above

Counter mobility obstacles – Such as mines should be very effectively cleared and destroyed by FAEs, as much like the aircraft section above the fuel is able to be dispersed evenly across the mine field and then detonated. An air blast from a conventional explosive may not have enough pressure across the whole field to effectively clear it

6. Conclusions

In this report there has been an explanation of the theory behind the phenomena of fuel-air explosions (FAE) and an identification of possible targets within the military environment, which could be defeated by such means. This includes personnel, buildings, grounded aircraft, possible stranding of armoured vehicles with the possibility of armour defeat and clearance of mine fields.

It has also been shown that as a weapon FAEs are really very flexible in nature and can be more powerful than conventional explosives. In summary FAEs offer a good variable and flexible return on investment.

Munitions – Thermobaric Munitions and their Medical Effects!

ABSTRACT

Thermobaric munitions are those munitions that, by design, produce more heat and overpressure than conventional explosives by exploding a vapour in the blast zone. Their main use initially was in airborne fuel-air explosive bombs. Whilst the United States has concentrated on airborne weapons, Russia has produced thermobaric weapons and warheads, from airborne bombs to rifle grenades.

Their medical effect is principally primary blast and they affect organs where there is a tissue interface of varying densities, such as the lungs, bowel and inner ear. Damage manifests itself in the severity and onset of occurrence, depending on distance from the blast and orientation of the victim, and can be diagnosed by simple investigative techniques.

This paper was originally written as a presentation for the Australian Military Medical Association Annual Conference in October 2001 and was displayed as a poster at the Defence Health Symposium in 2002.

INTRODUCTION

Thermobaric munitions are those weapons that are designed to produce enhanced temperature and pressure compared to conventional explosives and are often referred to as fuel-air explosives (FAEs). They produce a much greater incidence of primary blast injury than conventional explosives and this is their main mechanism of injury

This first part of this paper will discuss the history, design, and weapons employed to deliver thermobaric munitions. The second will discuss the medical effects and treatment, concentrating on the sequelae of primary blast injury

HISTORY

Thermobaric munitions can be traced back to the German Army of World War II who used a six barrelled 15cm Nebelwerfer rocket launcher on the Eastern Front. One of the launcher's loadings incorporated propane gas. The first five rounds carried the gas and the sixth was the detonating round. This gas was released when the round landed, mixed with the air to produce an explosive vapour, and was then detonated by the final round¹. At a later stage, larger calibre rockets contained conventional explosive inside a thin wall to give an increased blast effect. Following these early attempts, little was developed until the 1960's.

The United States started using FAEs during the Vietnam War² and had various loadings of aircraft bombs. The Soviet Union started using thermobaric weapons during their war in Afghanistan and the Russia has used them more recently in Chechnya. Russia has loadings in aircraft bombs and rockets, and ground launched rockets down to a man portable size³.

DESIGN

Thermobaric munitions work by initially dispersing an aerosol cloud of gas, liquid or finely powdered explosive. Known fuels such as ethylene oxide, propylene oxide¹, ammonium nitrate², and powdered PETN⁴ have been reported. This cloud flows around objects and into cavities and structures. It may penetrate small openings, such as openings in buildings, bunkers and engine bays of armoured vehicles¹, before being ignited.

The result is a plasma cloud that reaches temperatures of between 2,500-3000° Celsius⁴. The time that the cloud burns is slow compared to conventional high explosive and aluminium powder is added to some explosives to enhance this⁵. It is this longer duration or dwell time of the blast wave or overpressure, which can be up to 73 kg/cm² (1000 lb/sq in), that is the main reason for its lethal and destructive effects⁴. The injuries are more severe in confined spaces as the blast wave reflects back and forth, submitting the target to multiple insults.

One should not forget the burning effects of the explosion either, as it consumes all oxygen in the area and the resultant vacuum pulls loose objects into this void⁴. If the explosive does not detonate, the affected area can be

highly toxic, as one of the common fuels used is ethylene oxide. Ethylene oxide is a gas used as a sterilising agent in the health industry and is extremely toxic if inhaled⁶. This may lead to accusations of the use of chemical warfare if this situation were to occur.

WEAPONS

The employment of thermobaric munitions starts at the soldiers' level with Russia using RPO-A Shmel disposable rocket launchers and thermobaric rockets for the RPG-7 family of weapons. The effectiveness of the Shmel round has been compared to the 122mm artillery round, especially against buildings⁷. There is also a 42mm hand held magazine grenade launchers.

Next in line are the anti tank rocket launchers that are either wire or radio guided and include the Shturm, Ataka, Fagot and Komet systems. The Shturm and Ataka can also be helicopter launched³.

The USSR has been fond of multiple ground launched rocket systems since Stalin and this tradition has continued since. There are Uragan and Buratino 220mm launcher systems and the 300mm Smerch rocket systems³. Airborne weapons include the 80mm S-8D and the 122mm S-13D unguided rockets, 500 kg ODAB- 500PM bomb, the KAB-500kr-OD television guided bomb and the ODS-OD BLU dispenser with BKF ODS OD-cluster bomblets³.

The United States has the CBU-55 cluster bomb², the BLU 96 guided glide bomb¹ and, the granddaddy of them all, the BLU 829. The BLU 82 is a high blast bomb launched on a pallet from the back of an USAF MC-130H Combat Talon (Hercules) Aircraft and it was first used in the Vietnam War². It contains 5715 kg of a jellied slurry explosive called GSX, a mixture of ammonium nitrate, aluminium powder and polystyrene soap, and produces an overpressure of 1000 lb/sq in. It is reported to be able to clear a 3 mile path through a minefield⁹. It is often launched in pairs giving these weapons the title of the 'Blues Brothers'¹⁰.

In the war against terror in Afghanistan, the United States used a new generation of thermobaric bombs, the BLU-118/B11. It is the BLU-109 2000lb penetrating warhead with a thermobaric filling of 560lb, and can be fitted with a laser guidance or glide bomb kit¹². A warhead for the Hellfire missile has also been developed¹³.

PRIMARY BLAST INJURY MEDICAL EFFECTS

Primary blast injuries are those caused by a blast pressure wave or blast wave^{14, 15, 16}, which emanates from the epicentre of the explosion at a pressure of thousands of pounds per square inch¹⁴. Normal atmospheric pressure in comparison is 14.7 pounds per square inch¹⁷. Gailbraith¹⁸, describes this phenomenon as a combination of shock wave¹⁵, and dynamic overpressure, and damage is dependent on the pressure and length of its duration¹⁶.

This causes disruption of air spaces in the body and shear forces where there is an air /tissue interface or where tissues of different densities connect^{16,19}.

It predominantly affects the pulmonary, cardiovascular, auditory, gastrointestinal, and central nervous systems. General treatment is based on airway; breathing and circulation assessment, in conjunction with oxygen therapy. Prophylactic antibiotics¹⁶ and tetanus vaccine¹⁴ should be considered. Follow up should be done at a medical facility.

PULMONARY SYSTEM

Mellor et al.¹⁶ describe the mechanism of injury; when the blast wave hits, as dependant on the bodies alignment to wave and when it passes through tissue interfaces. This sets up a stress wave that causes damage, particularly at the lobes, along the ribs on the side of the blast, mediastinum and alveoli, and, if low velocity; may rupture the more rigid bronchioles. The alveoli, if ruptured, leak fluid into the lungs, which could lead to complete filling or 'shock lung' or 'blast lung'¹⁸. Other complications of alveolar rupture are arterial gas embolisms^{14,19}, pneumothorax and/or haemothorax¹⁴. Mellor et al.¹⁶ note that respiratory distress related to a non-fatal injury may not present for several hours, with Armstrong ¹⁴ suggesting 48 hours.

Treatment first requires assessment by continuous auscultation, to detect abnormalities, as well as continual assessment of rate and depth of respiration and pulse oximetry to assess pulmonary function¹⁴. Mellor et al.¹⁶ add serial blood gases and erect chest radiographs, and oxygen therapy and chest drain if a pneumothorax or aemothorax is present.

CARDIOVASCULAR SYSTEM

The cardiovascular system may be affected by an air embolus in the heart or coronary arteries^{16, 18}, or by diffuse damage to the myocardium¹⁶. Sharpnack et al. describe a post mortem sheep's heart with extensive epi and sub-epicardiac haemorrhage after exposure of a live sheep to blast overpressure.

Symptomatic treatment is required and detection is the key. Auscultation for bruits, indicating vascular leakage, and for faint heart tones, indicating cardiac tamponade, and monitoring ECG changes, that might indicate heart damage, is required^H.

AUDITORY SYSTEM

Gailbraith¹⁸ describes auditory damage in stages. In mild damage, the tympanic membrane is ruptured^{15, 19}, with mild hearing loss. In more severe cases, the membrane could disintegrate and the ossicles dislocate, requiring surgical intervention. In the worst cases, the inner ear is damaged producing 'sensori-neural' deafness and disabling pain, nausea and balance problems. Mellor et al.¹⁶ concur and add that dislocation of the ossicles may occur without tympanic rupture, the organ of Corti is most at risk and labyrinthine rupture will lead to dizziness and vertigo. Investigating a patient's ears will detect damage^{14, 18}. In mild cases, the ears should heal naturally but, in more severe cases, surgery is required¹⁸.

GASTROINTESTINAL SYSTEM.

Mellor et al.¹⁶, feel gastro-intestinal damage is probably more common than is diagnosed and occurs when stress waves cross pockets of gas trapped in the bowel. Bruising occurs in mild cases¹⁵ but, in severe cases, perforation may occur, particularly at the ileocaecal junction¹⁶. Monitoring for peritonitis, due to leaking bowel contents¹⁸, and haemorrhaging is required^H. This can occur up to 14 days after the injury¹⁸. Treatment for the perforations and haemorrhage is surgery¹⁸, and close monitoring is required to detect these injuries and their complications^H.

CENTRAL NERVOUS SYSTEM

The main injury to the central nervous system from primary blast is a cerebral arterial gas embolism and this may cause an unexplained deterioration in function or death¹⁸. Sharpnack et al.²⁰ describe a post mortem sheep's brain exposed to blast overpressure showing air emboli within the basilar artery and posterior portion of the arterial circle of the brain.

Hyperbaric oxygen therapy is the main treatment and 100 percent oxygen if this is not available²¹. Detection is by closely monitoring the patient's level of consciousness and peripheral nerve function¹⁴. In these cases, air may be seen in the retinal vessels¹⁶.

CONCLUSION

Thermobaric weapons have been around for over sixty years and their main damaging effect is through primary blast injury. The mechanism and treatments for primary blast injury have been described, and it can be seen that a patient may have more than one system involved¹⁸.

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