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THE THEORY AND APPLICATION OF FUEL-AIR EXPLOSIONS

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Abstract

A study of fuel-air explosives (FAE) has been conducted using science journals, books, and case studies from commercial and military domains. The following topics are discussed: FAE definition followed by reported incidents within the industry; examples of fuel-air weapons; operation of FAE weapons with attention to critical design features; shock wave and blast wave theory for conventional high explosives (HE); a comparison of FAE shock wave and blast wave against HE; and finally suitable targets for FAE weapons.

It was determined that FAE have better blast characteristics and application against lightly armoured ground targets compared to HE. However, FAE weapons are more complicated in design (thus more reliability issues) than HE and have limited applications.

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Introduction to Fuel Air Explosives

A fuel-air explosive is a fuel burning in the air. The fuel can take different forms, either being a dust, vapour, gas, or hybrid mixture. The fuels can be a variety and mix of common combustible materials such as natural and synthetic organic compounds, metals, and hydrocarbons. [1] However, in the combustion of the fuel, if the energy release and production of gases are fast enough, it can lead to an explosion causing damage.

Due to the common materials, FAE are a common hazard within the industry. To control and mitigate FAE hazards, the Health and Safety Executive created The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002. [2] Which aims to control the creation of explosive atmospheres and avoid ignition. This is due to the devastation FAE can cause.

Industry Case Studies

- **Flixborough, 1974, Gas Explosion**

50 Tons of cyclohexane mixed with the air and found an ignition source. Due to the confinement from the machinery plant, an explosion occurred equivalent to 16 tons of TNT. 28 people died on site, 36 injured on site, and 1988 buildings were affected. [1]

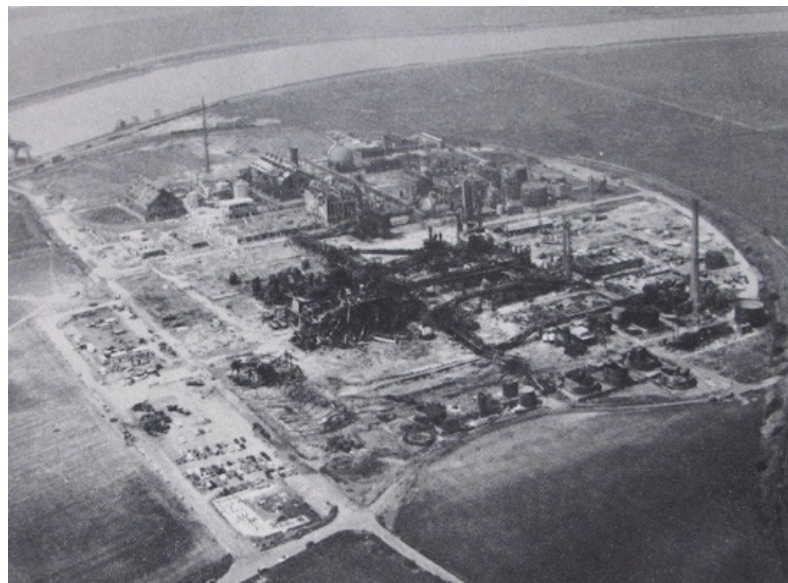


Figure No.1 – The plant after the explosion [2]

- **Texas City Refinery Explosion, 2005, Vapour Explosion**

An over pressurised vessel released hydrocarbons which started to pool at the base of the vessel. The vapours from the hydrocarbon mixed with the air and produced a vapour cloud. The cloud reached a local idle diesel pick-up truck, and the engine provided the ignition. Overall, 195 people were affected (15 Injured, 180 severe injuries) and an area of 19000m² was severely damaged. [3]



Figure No.2 – Damage after the explosion [4]

- **West Pharmaceutical, 2003, Dust Explosion**

An extractor fan was poorly maintained which collected combustible polyethylene dust from a rubber machining process. Due to the engineers failing to realise the hazard, the dust collected was disturbed creating a dust cloud which ignited. Upon investigation, the source of ignition could not be identified due to the damage. Overall, windows 300m were shattered, and debris was propelled 3.2 Km from the site. [3]



Figure No.3 – Damage after a dust explosion [5]

It can be seen from Fig.No 1 – 3, FAE explosives can provide deadly effects from blast and heat. Damaging vast areas and causing secondary effects such as fires. Due to these desired effects for military applications, there have been developments towards FAE Weapons.

Military Case Studies

- **CBU-72, Origin: American, Targets: Mine Fields, Entrenched Personnel**

In the Vietnam War, these munitions used a cluster of three sub-munitions filled with 34 kg of ethylene oxide. They would disperse the gas in an 18m diameter and 2.4m high cloud, 9.1m above the ground. A delay charge would detonate the fuel to create a blast effect and intense heat. [5]



Figure No.4 – Picture of the American CBU-72 [6]

- **RPO-A Shmel, Origin: Russia, Targets: Entrenched Personnel, Light Vehicles**

Used in Afghanistan and the first and second Chechen wars, this munition is an 11 kg shoulder-launched missile with a 2 kg charge. It's reported it can produce a 6m fireball and a 50m blast area. One source claimed it has the power equal to a 152mm artillery shell! [6] [7]



Figure No.5 – RPO A Shmel launcher and munition [7]

FAE Weapon Operation

A FAE weapon is a two-stage system that works in the following:

- First, the fuel is scattered to create an ignitable cloud.

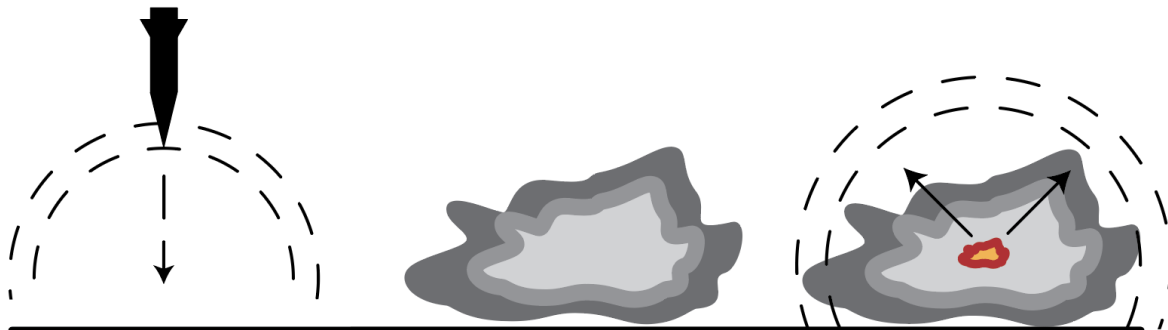
This is usually achieved with an explosive burster charge. During the dispersion of the fuel, it goes through three stages: [acceleration, deceleration, and turbulence](#).

Acceleration: The fuel increases in velocity and travels radially from the burster charge and separates into smaller particles.

Deceleration: Air drag, and particle size will reduce the velocity of the fuel travelling radially until the fuel particles come to rest.

Turbulence: The fuel particles then roll locally, meaning the cloud will become more uniform with the air, mixing homogenously. At this point, the cloud does not grow anymore.

- After a delay, to allow the fuel to disperse and mix, a secondary explosive event occurs. This is to create a shockwave which will compress and heat the fuel and air particles in the cloud to create a detonation in the air-fuel mixture. Resulting in high pressure and heat. [8] [9] [10]



First a cloud is dispersed from the munition. Then a secondary delay charge ignites the cloud causing detonation of the fuel.

Figure No.6 – Visually diagram to show how Fuel Air Explosive Operate

The following are critical Design Parameters for the:

Dispersion of the cloud

- Design of the Cannister
- Burster Charge

Ignition of the cloud

- Heat of combustion
- Lower and Upper Flammability levels
- Stoichiometry
- Ignition Temperatures

Dispersion of the Cloud

Height to Diameter Ratio

Work has been conducted to determine the optimal height to diameter ratios for the dispersion of fuel. By varying the height and diameter of the fuel, the formation of the cloud can be affected as well as maintaining pressure over a sustained distance.

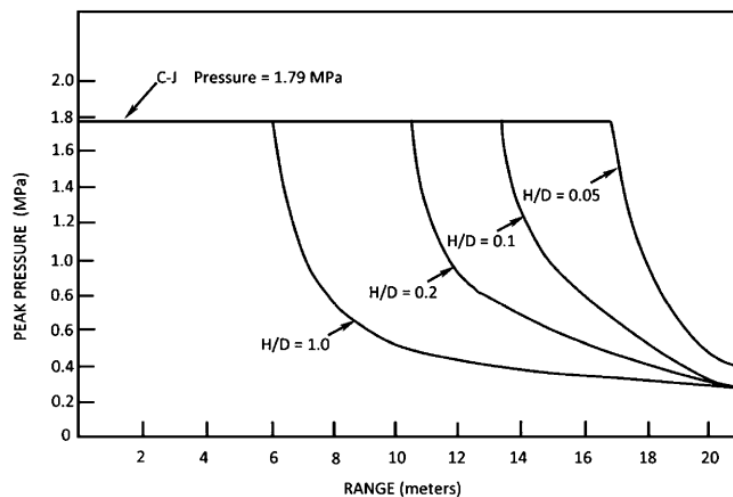


Figure No.7 – Pressure against distance of a FAE with varying H/D ratios [11]

Figure No.7 shows that by reducing the ratio between the height and diameter of the fuel charge, this can result in a greater peak pressure over a greater distance. However, the rate of decay increase.

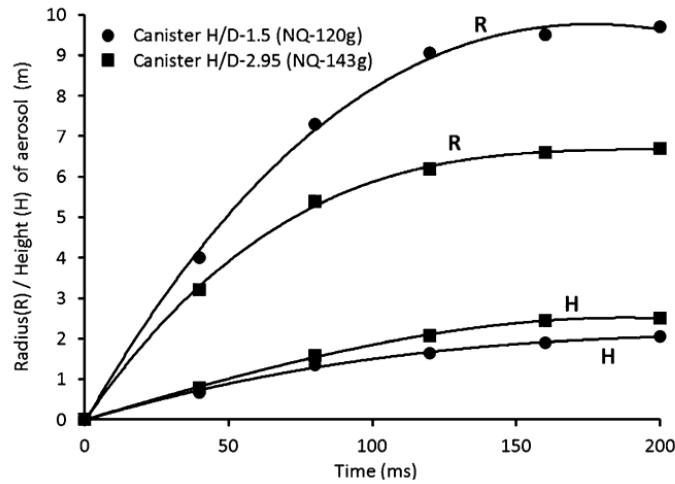


Figure No.8– Radius and height of fuel dispersion with varying H/D ratios [11]

Figure 8 shows by varying the H/D ratio different dispersion volumes can be achieved. This can later be used in creating an optimal cloud, in which a stoichiometric mix can be utilised. Additionally, by being able to create a larger cloud in less time this will affect the secondary delay fuze. If a greater volume can be achieved faster, then there will be a less of the delay.

Similarly, Figure 8 correlates with Figure 9, showing different H/D ratios will also affect the velocity of the fuel dispersion. Hence a reason for the difference in cloud radius and height, is due to the difference in fuel velocity during dispersion.

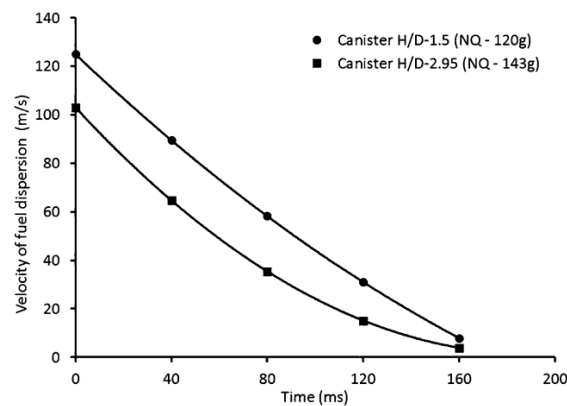


Figure No.9 – Velocity of particle dispersion against varying H/D ratios [11]

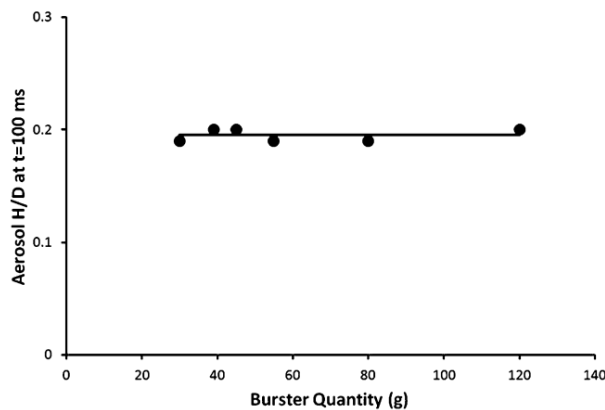


Figure No.10– Cloud H/D ratio from different burster masses [11]

Interestingly, it was recorded by Allam Apparao and Chillarige Rao that the change in burster quantity had no effect on the dispersion of the fuel. This agreed with an alternative source [], in which said by increasing the burster size the dispersion would reach a maximum point due to the drag from air increasing during the declaration of the cloud phase. While decreasing the burster would result in larger particles which would have greater inertia during the acceleration.

Overall, there is a maximum aerosol (cloud) size the burster charge can achieve. Too weak, and there is risk the particle size is not fine enough. Too much, and there is risk of autoignition from the explosive power of the charge.

In summary, the height and diameter ratio of the charge will affect the overall performance of generating the fuel cloud. With a lower H/D ratio, greater dispersion area, dispersion velocity, and fragmentation of the vessel can be achieved leading to a greater lethality.

Burster Explosive Charge

The mass of the explosive charge is important for the dispersion of the of the fuel. While Allam Apparao and Chillarige Rao, discovered that the mass of the burster charge does not affect the H/D ratio of the cloud, the burster still needs to achieve two functions.

- Break-up of the munition casing
- Break down the fuel into a cloud
 - For liquids and solids, to also break down into smaller aerolised particles

To achieve this energy is required for both functions from the burster charge. Figure 11 shows a fuel being dispersed by different burster charge materials. If the burster charge is too powerful, it can lead to early autoignition. As a result, this would lead to incomplete combustion of the fuel. Therefore, a less powerful burster charge may be required. Additional, features such as fleshless bursts would be beneficial to reduce the ignition of the fuel during dispersion.

Overall, the burster design is a balancing act to ensure the break-up of the casing and maximum dispersion of the fuel. While also reducing the power to ensure the fuel is not ignited or used in the combustion of the burster.

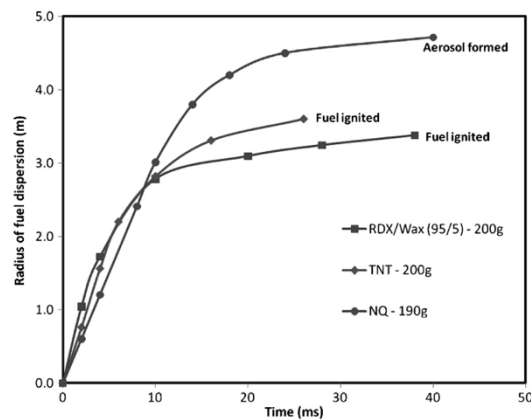


Fig No.11 – Fuel dispersion pattern of 4.3Kg propylene oxide using RDX, TNT, and NQ burster charges [8]

Ignition Process

Heat of Combustion

The energy release from solid fuels is greater than high explosives. For example, Table 1 shows hydrocarbon chains and metals having more energy than a high explosive.

Fuel	Q (kJ/kg)
TNT (solid explosive)	4200
Ethyne	5000
Aluminium (dust cloud)	16000
Ethylene oxide (vapour)	21000
Gasoline (aerosol)	37000
Propane	38000

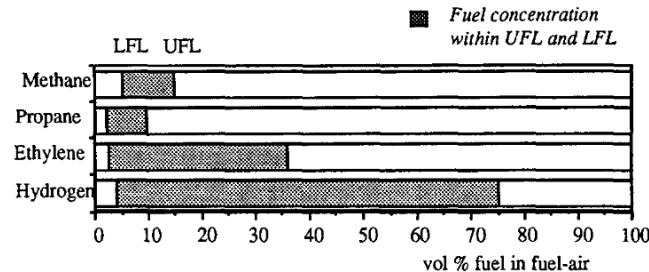
Figure No.1– Energy densities of different fuels compared to TNT [12]

However, to utilise the fuel in an explosive environment an oxidiser is required. Unlike the hydrocarbons, TNT has oxygen within the molecules and can self-sustain itself once ignited. Overall, once the fuel is ignited, more energy will be produced from the combustion of a FAE compared to a HE. Although, the rate of energy release will be greater for a HE, compared to a FAE. This will result in HE having greater peak pressure.

Lower Flammability Levels and Upper Flammability Levels

A premixed fuel-air mixture will only burn if the fuel concentration is between the upper and lower flammability levels. Therefore, before the fuel can be ignited the dispersion process needs to adequately mix the fuel with an oxidiser. This will enable an adequate mixture between the oxidizer and the fuel which can then sustain a burn.

Fig No.12 – Flammable ranges for fuel-air mixtures at 1.atm and 25 degrees [1]



From Figure 12, hydrogen shows a wide range of vol percentage when in air. While a large difference in LFL and UFL may be useful for the reliability of ignition, this could increase the sensitivity of the munition. As such this may result in a deflagration of the munition from the burster charge rather than a detonation.

A factor which can affect the LFL and UFL is temperature. The greater the temperature of the gas, the greater the difference between LFL and UFL. Using Fig.13, this shows if the temperature is too great, autoignition can occur. This would then affect the burster design to ensure temperatures are not too great during the dispersion. Therefore, explosive compounds without aluminium, should be used to reduce heat of combustion.

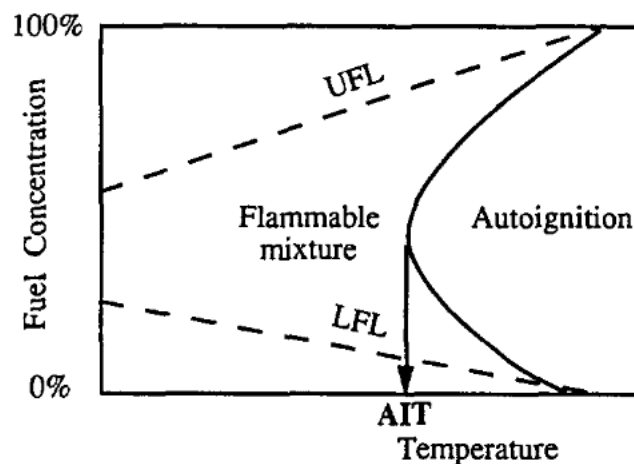


Fig No.13 – Autoignition zone against temperature and Fuel concentration [1]

Stoichiometry

To achieve the maximum utilisation of the fuel's entirety, a complete reaction is required by oxidising all the fuel in a combustion processes. As a result, there needs to be an oxygen balance of the fuel and the ambient air. This may create requirements for the dimensions of the cloud size, as there is only 21% oxygen in the air. Therefore, surrounding air may be sucked, creating a vacuum, into the combustion to continue the combustion of the fuel.

If there is no excess fuel or oxygen after the reaction, then the maximum amount of energy has been released. Thus, achieving the highest release of energy and as a result blast and heat effects.

Minimum Ignition Energy (MIE)

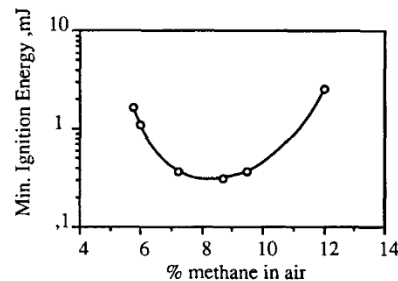


Figure No.14 – Minimum Ignition Energy for varying concentrations of methane in air [1]

Figure 14 shows how the change in volume of methane in air, effects the minimum ignition energy required to ignite the mixture. This shows that the energy required varies with the volume of methane. As a result, affecting the timing, of the secondary explosive to ensure lowest MIE. By being able to wait for the lowest point for the minimum ignition energy, a smaller charge is required. Reducing energy required and improving reliability if a larger secondary charge is selected. By overmatching the MIE requirements this will improve reliability.

Particle Size

Another method to reduce the energy required to ignite the fuel-air mix is to reduce particle size. Studies have shown that finer aerosol mixtures of hexane are more sensitive, requiring lesser tetryl charge for initiation and produce higher velocity of detonation in the mixture. [8] Meaning by creating a finer cloud, less explosive power is required to detonate that cloud.

Chemical Behaviour

Another method of reducing the ignition energy, is by selecting chemicals with lower bond energies are more sensitive towards detonation. [8] This would then allow the cloud to activate more easily, if the energy threshold for combustion is less.

Optimal Ignition Design

Considering the effects of:

- Lower and Upper Flammability Limits,
- the stoichiometry of the fuel and air mixture and,
- Ignition Energy.

To ignite the fuel and air a timing element is required for the optimal dispersion of the fuel. This is to allow the fuel to reach it's LFL and UFL to allow propagation of ignition, while also allowing a stoichiometric mixture of fuel and air. This will provide the maximum amount

of energy towards fuel and blast. All while, achieving the optimal point for the least amount of energy required to ignite the mixture.

Shock and Blast Wave Theory

An explosion can occur when there is a sudden release of energy over a short amount of time. It does not always have to be chemical; it could be from overpressure of a system (Pressurised boiler), a fuel-air reaction, or an uncontrolled nuclear reaction. However, during an explosion there is the creation of a blast wave, and shock wave. Sometimes known as blast wind and shock front.

Deflagration and Detonation

If a shock wave is generated from an explosive reaction, then a detonation has occurred. If there is no shock wave generated, then the reaction is considered a deflagration.

Deflagration

Burns sub-sonically $< 343\text{m/s}$

Detonation

Rapid and violent reaction $> 343\text{m/s}$

The type of reaction is important for the release of energy for a FAE Weapon. If a reaction is subsonic, then the fuel will burn producing less pressure compared to a detonation, although remaining for a longer time. A detonation on the other hand will produce a shock wave, reducing the reaction time to combust the fuel. Therefore, generating greater pressures and heat.

Shock Wave

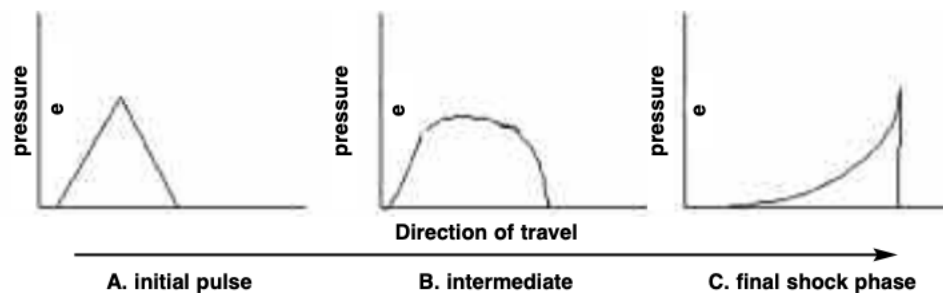


Fig No.15 - Development of a shockwave from an initial pressure distribution in air [13]

To visualise the shock wave, consider diagram A in Figure 15. Think of diagram A recording an idealised pulse of pressure. The pressure builds to its maximum and then dissipates as it passes. If the triangle was cut into sections, the area of the section would represent its velocity. As such the greater the area, the greater velocity of the section.

Diagram B in Figure 15 shows the start of the same graph. However, once the pressure has reached its peak, due to having a greater velocity (due to a greater section), the pressure is steeper. This is because the faster moving sections are moving faster than the slower moving sections.

Eventually, when both a low pressure (thus low velocity) and high-pressure overlap (high velocity) a discontinuity is formed, and a shockwave is created (diagram C. figure 15). Figure 16 shows a discontinuity being formed however using points to represent the formation.

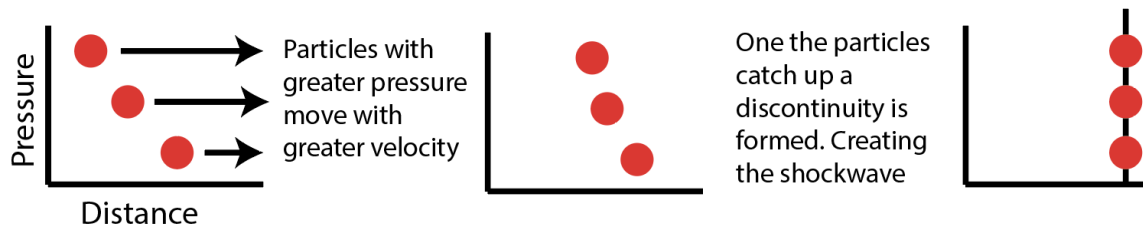


Figure No. 16 – Development of a shockwave

This shock wave is important for the ignition and affect for a fuel air explosive. As the shockwave will travel far, producing large amounts of heat and pressure, dumping energy into objects the shockwave encounters.

Blast Wave

Figure 17 shows an ideal blast wave. It begins with a sharp peak in pressure due to the shock front, followed by a rapid decay, falling into a negative pressure and eventually returning to atmospheric. The positive phase occurs in the milli-seconds, while the negative phase occurs in milli-seconds to full seconds.

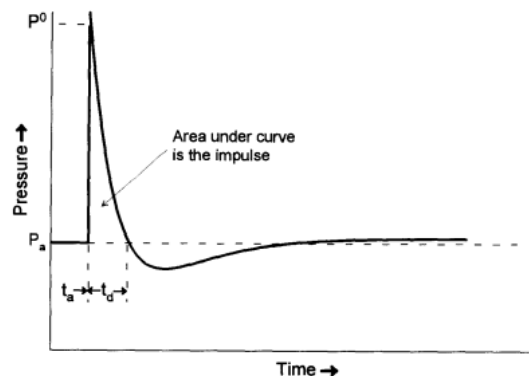


Figure No.17 – An Ideal Blast Wave [1]

The strength of the blast wave depends on the size, explosive material, and distance from the blast. Therefore, to increase the blast wave, more explosive can be used with greater explosive properties, while moving it closer to the target.

During the positive phase, the blast pressure rapidly decays due to gases expand in all directions, creating a rapid decay. The ambient air removed from the atmosphere by the blast, creates a negative pressure. As a result, a secondary force returns where air is being sucked back into the atmosphere which the explosive shock front removed. Thus, on structures both a positive and negative force is applied (Figure 18)

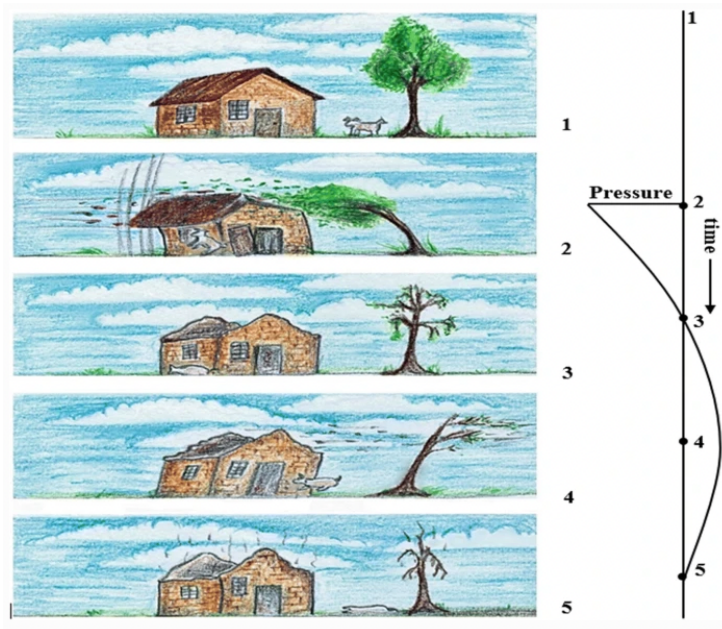
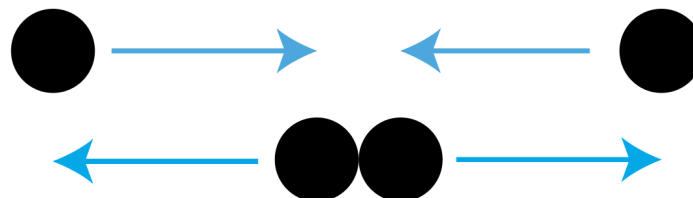


Figure 18 – Blast Wave affecting a structure [14]

For the calculation of damage, the positive phase is used. Measuring the area under the curve, the force applied over a time gives impulse.

Wave Reflection

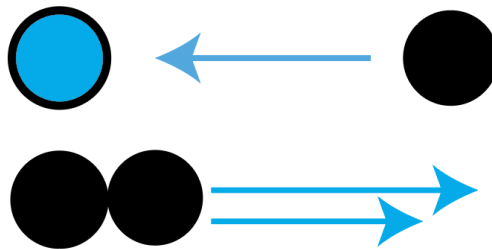
Like sound and light waves, shock waves can be reflected. In a linear-elastic collision the particles would collide, and bounce with equal pressure. Like two billiard balls moving towards each other with equal velocity and mass and bouncing off each other with equal momentum.



Conservation of momentum with equal mass and velocity for both billiards will result in an equal reflection.

Figure No.19

However, a shock wave is non-linear. Imagine a billiard ball fixed, however containing energy. When the second billiard ball collides with the first, the reflection will be of greater magnitude as the second billiard ball steals the energy from the first. In summary, the reflection of waves is greater.



The left billiard cannot move but has potential energy. Upon collision because the billiard cannot move the energy is transferred. Giving the second billiard more energy (Pressure and Velocity for explosives).

Figure No.20

As a result of this reflection, blast waves are highly effective when reflections can be introduced. This is because the peak pressure would increase and as a result impulse. Additionally, the blast can be reflected around corners, and rooms or caves. Making blast weapons effective enclosed or confined areas.

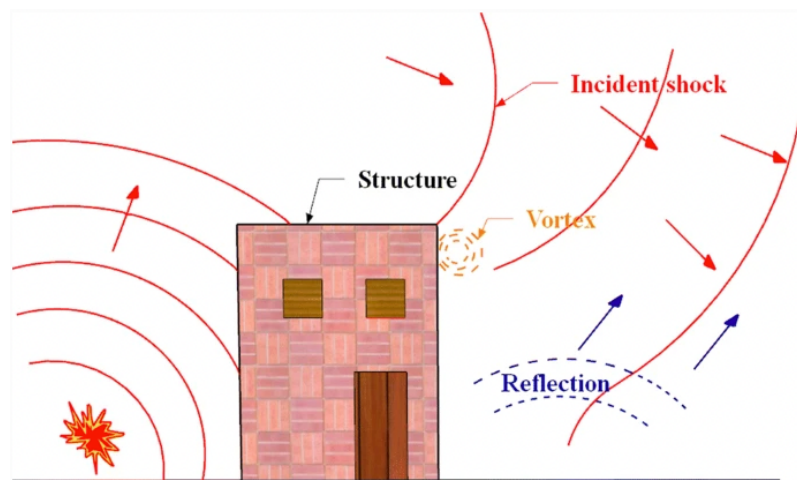


Figure No.21 [14]

FAE Shock and Blast Wave

Above discussed the formation of a shock and blast wave produced by conventional high explosives (HE). Figure 18 compares the pressure and duration against range for both fuel air explosives and a high explosive.

It can be determined that HE can produce the greatest pressure compared to a FAE. However, the FAE has a greater pressure, for a longer duration over a greater range compared to HE. Therefore, producing a better blast effect. This is due to the greater impulse, meaning more energy can be applied to defeating targets over a wider area. As a result, the accuracy of the system can be reduced. However, the design complications to achieve a FAE detonation are

more when compared to HE. Additionally, FAE rely on an oxidiser in the air to react. Therefore, limiting the applications in theatre.

Although not show in the graph, due to a greater pressure over a greater distance and time for FAE, the ambient air displaced would be greater, compared to TNT. Therefore, leading to a longer and greater negative phase.

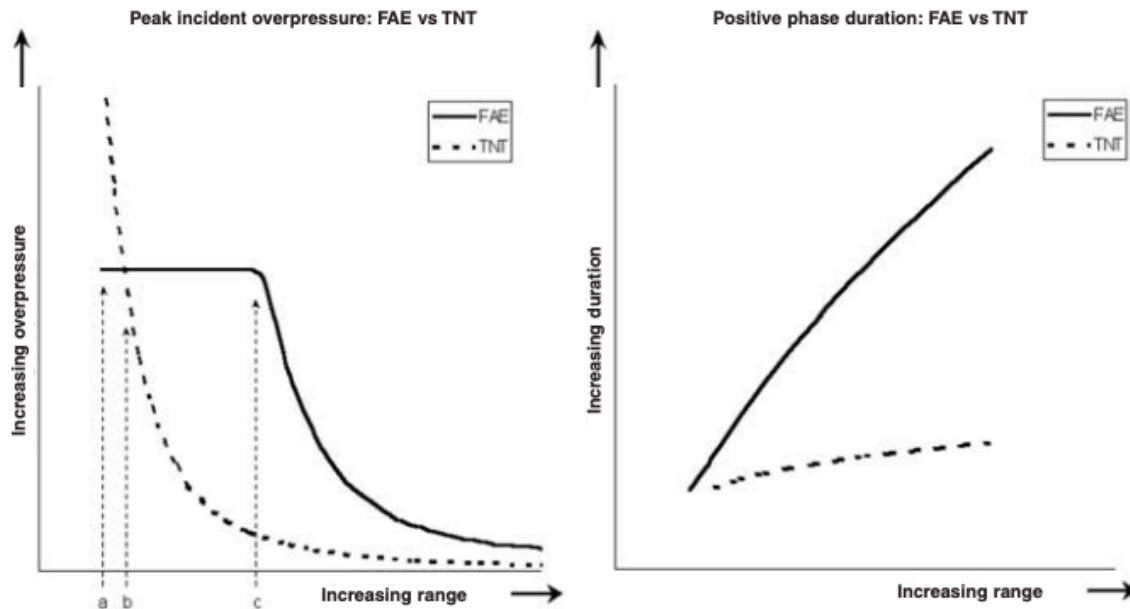


Figure No.22 – Overpressure and blast duration for 1kg TNT and 1Kg Ethylene Oxide [7]

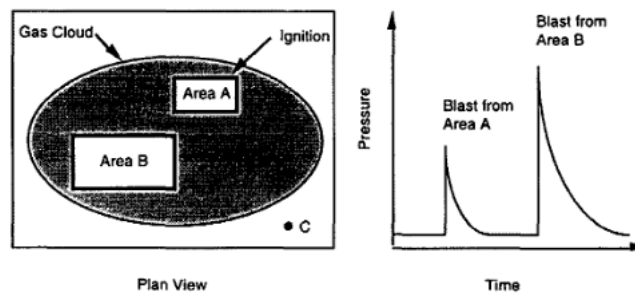


Figure No.23 – Gas cloud causing multiple detonations [1]

Unlike HE, FAE has the chance to have multiple detonations.

If there is a deflagration this can propagate until the flame reaches an area of confinement in which a burn to detonation transition occurs. Figure No.19 shows an cloud burning, however when the propagation area a and b, due to confinement a blast occurs.

This could be argued as a disadvantage due to potential energy being lost to the deflagration rather than a whole detonation and maximum use of the energy.

Weapon Applications

In summary from the previous chapters FAE have the following advantages over traditional HE.

- Greater sustained pressure over distance compared to HE
- Greater impulse than HE
- Greater energy per unit mass compared to HE

However, the disadvantages of FAE are:

- Lower Peak Pressures compared to HE.
- Reliability, due to critical parameters required for detonation
- Limited Fragmentation damage, and therefore penetration capabilities.
- Relies on secondary delay charge and an oxidiser in the air.

From these considerations arguments will be made for FAE on the following targets: Armour, Aircraft, Ships, Personnel, Fortifications and Structures, and minefields.

Target	Application Argument
Armour	Against heavy armour such as main battle tanks, FAE will not be effective due to the lack of penetration power. However, it is suspected to be effective to disrupt operators and remove defensive aids suits. Against light armour vehicles, FAE are considered to be effective.
Aircraft	Despite being able to maintain pressures at greater distances, due to the target being in an environment with no oxidiser - little to no affect will be achieved.
Ships	Similar to MBT's, an external blast will have limited effect on surface vessels. Damaging external structures and disorienting local crew. As there is no oxidiser underwater, no FAE will operate.
Personnel	Against personnel in open spaces, FAE will be highly effective compared to HE. This is due to a greater area of effect, greater positive phase, and negative phase impulse, as well as secondary effects such as heat. Personnel in entrenched positions, such as fortifications, or underground mines are at greater risk. This is due the blast wind being reflected and magnified along the tunnels. Additionally, due to the dispersion of small particles these can seep past obstructions through cracks and vents. [14]
Fortifications and Structures	Heavily fortified buildings and positions will remain untouched by the effect of FAE despite the greater positive and negative impulse. However, civilian buildings will be greatly affected.
Minefields	There has been debate on the effectiveness of FAE against minefields. Some authors say conventional FAE (hydrocarbon fuels) are not effective, however RDX FAE are effective. Overall, FAE can be utilised against minefields to increase chances of clearing obstacles. However, the fuel must be matched against the pressure activation threshold of the mine. [15] [16]

Table. No 2 – Military Applications for FAE

Conclusion

From the study of FAE weapons, the following conclusions have been made:

- Despite being a hazard within industry, FAE weapons are more effective than traditional HE when used against lightly armoured ground targets. This is due to having better blast and heat performance. With greater pressures being maintained for a longer duration over a greater distance, generating a greater positive and negative impulse. However, if a great peak pressure is required than FAE are not suitable.
- The disadvantages of FAE compared to HE is that FAE have limited applications due to the requirements to generate a fuel-air cloud. Therefore, not being suitable underwater, or at high altitudes where there is little to no oxidiser.
- FAE compared to conventional HE, have a more complex design to generate a detonation of fuel. With factors such as, stoichiometry, LFL, UFL, minimum activation energy, cloud dispersion, burster design all affecting the performance. As such reliability and cost for development will be greater.
- Finally, it was determined, FAE are effective against the following targets: personnel both in the open and entrenched, structures, minefields, and lightly armoured targets.

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