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The theory and application of fuel-air explosives

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Abstract

Fuel air explosives are capable of producing far more powerful impulses than their conventional counterparts. Although the mechanisms for fuel-air explosions have been understood for centuries through the occurrence of industrial accidents, it is only relatively recently that they have been used in munition design. Since their introduction in the 1960's they have become more refined and prove excellent options for modern militaries to deal with a wide range of targets including structures and personnel, as well as being able to be used in specialist applications such as mine-clearance.

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History and overview of fuel air explosives

Fuel air explosives (FAEs) have been well documented throughout history in the form of industrial accidents and so are not a new phenomenon. Several instances where a fuel cloud consisting of vapour, gas, or a fine powder mixed with air have been ignited - resulting in an explosion. Accidents such as Flixborough or Buncefield [1] in the UK are prime examples of how devastating a fuel-air explosion can be. In both of these cases a large amount of fuel vapour was able to mix with the air and resulted in very large explosions that caused massive amounts of damage to buildings and infrastructure, and lead to the loss of life at Flixborough [2].

Recorded accidents involving fuel-air explosions date back as far as 1785 when an Italian bakery suffered from a resulting from a cloud of flour next to an oven. Many other examples exist involving mills, store houses and other industrial plants. [3] The use of fuel-air explosives applied for military use does not occur until the 1960's although some sources say that Nazi Germany may have been developing fuel-air weapons as early as the closing days of WW2. [4] In the 1960's America developed fuel-air explosive devices, this was followed swiftly by Soviet development. The Americans developed munitions such as the 500lb CBU-55B cluster bomb. [5] The Soviets soon developed their own fuel-air munitions such the RPO-A. [6] Both America and the Soviets (Later the Russian federation) have continued to refine fuel-air and thermobaric weapons alongside other nations, with them being used in several conflicts around the world. [7]

The theory of fuel air explosives

To understand why FAE explosions can be so devastating, first the mechanisms of a fuel-air explosion need to be understood. An explosive is generally comprised of two components, a fuel and an oxidiser. These two components react together rapidly to release energy forming explosive reaction products. In some cases, an explosive is a single compound that decomposes into multiple products to release its energy (these are referred to as molecular explosives or monopropellant explosives). [8]

FAEs differ from conventional explosives in that they consist only of the fuel component and rely on atmospheric oxygen to react and form products. Hence the "fuel-air" aspect of the name. Fuel is distributed into the air to form a cloud of dust, gas, or vapour/aerosolised liquid. Once ignited this cloud rapidly combusts forming a fireball, and if the conditions are right, this rapid combustion can propagate into a detonation wave as the fuel reacts with atmospheric oxygen. In industrial accidents clouds of dust or vapour are to be avoided and occur due to a failing in some process or component which leads to a fuel cloud forming. When coupled with an ignition source, a fuel-air explosion occurs. [9]

To harness this affect for use in munitions an ignitable cloud must be created in a short timeframe generate a fuel-air explosion. Achieving this involves the use of a conventional explosive to act as a burster charge which can disperse fuel into a cloud when a munition reaches a target. A secondary explosive device is then used to ignite the dispersed fuel to generate a fuel-air explosion. The burster charge must be large enough in magnitude to sufficiently disperse the fuel into an appropriately sized cloud, and the ignition explosive must be delayed by a suitable amount of time so that premature ignition is not attempted, nor that it initiates after it has cleared the cloud. [10]

Factors affecting fuel-air explosions:

- Fuel – FAE fuels can include any of the following: corn-starch powder, metal powders, liquid vapour or aerosols, any type of combustible gasses. The fuel is what reacts with atmospheric oxygen to produce the explosive reaction, therefore the choice of fuel will determine how much energy is released during deflagration/detonation. [11]
- Particle size – In general smaller particle sizes react more vigorously with oxygen due to having greater surface area. Whereas larger particle sizes have the opposite affect. [9]
- Saturation level – a fuel-air explosive mixture will only undergo deflagration/detonation if the concentration of the fuel in air is between the lower explosion limit (LEL) and upper explosion limit (UEL). In some literature these are referred to as flammability limits rather than explosive limits and so the acronyms LFL and UFL may be seen instead. [11]
- Atmosphere low/high altitude – atmospheric conditions will affect the performance of a fuel-air explosive device. As FAEs rely on atmospheric oxygen to undergo combustion, the amount of readily available oxygen will affect the stoichiometry of any potential reaction. As altitude increases the density of air decreases and therefore the concentration of oxygen also decreases. The fuel-air ratio increases and if this continues then the upper explosion limit can be exceeded. However, this increasing of the fuel-air ratio could promote explosion in a situation whereby the lower explosion limit has not yet been reached at ground level. An example of this is TWA flight 800. [12]
- Environment – environmental conditions may affect the ability of a fuel-air explosion to occur. Initially it should be noted that oxidiser rich atmospheres can also facilitate fuel-air explosions in the absence of oxygen. This is usually only an issue for processing environments where large amounts of oxidisers such as NO or NO₂ are present. In the case of munitions, factors such as wind speed or air density (foggy conditions for example) may affect the cloud formation and dispersion of fuels. [11]
- Initiation energy – A minimum shock energy is required to cause detonation in a fuel-air mixture. Below these energies, only combustion will occur. [5]

Experiments have been conducted that show combinations of energetic metal powders combined with liquid fuel can enhance both the heat of explosion and the blast wave overpressure. By the use of additions fuel-air explosives can be effectively tuned to whatever intended effect is required. [13]

Comparison of fuel-air explosive vs conventional explosives

As discussed, the primary difference between conventional explosives and fuel-air explosives is the lack of an oxidiser to achieve rapid combustion/detonation in the case of fuel-air explosives. Instead they react with atmospheric oxygen to achieve detonation. Despite both types of explosive being able to achieve detonations, there are clear distinctions in their performance and effects to be understood. Conventional molecular explosives such as TNT or RDX have relatively high velocities of detonation and generate high overpressures when detonated. Conversely, fuel-air explosives' velocities of detonation are lower as well as the peak overpressures. The important difference is that heat of explosion (usually denoted by "Q" in the literature) is much higher in fuel-air explosions alongside the duration of the positive pressure phase, referred to as "positive impulse" [6] [14]. See figure 1.

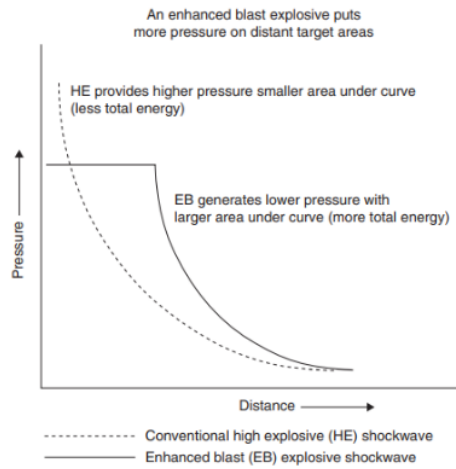


Figure 1- blast pressure/time curve showcasing conventional vs enhanced blast explosive [14]

Impulse is defined as the magnitude of a force applied to an object or system, multiplied by the duration of time it is applied for. On a force (or pressure) against time graph, this is represented by the area underneath the curve. [14]

This distinction is important as impulse is a much greater factor when imparting damage to structures compared to the peak overpressure.

Not only are fuel-air explosives able to produce such large impulses they are also able to do so with much less mass. For example the below table 1, shows that the Q per unit mass or “specific heat of combustion” is higher for fuel-air mixtures than it is for the Conventional explosive of TNT:

Fuel	Q (kJ/kg)	Ease of initiation
TNT (solid explosive)	4200	Secondary explosive
Ethyne	5000	Easy
Aluminium (dust cloud)	16000	Difficult
Ethylene oxide (vapour)	21000	Easy
Gasoline (aerosol)	37000	Moderate
Propane	38000	Moderate

Table 1- heats of explosion for various fuel-air explosives compared with TNT Taken from [6]

Military application of fuel-air explosives

Now that the theory of fuel-air explosions has been established and the mechanism for damage understood, the military application of the explosive effect can be explored. Several of the points raised regarding the theory of fuel-air explosives are pertinent to their application in a military setting:

These factors are:

- The ability to generate large impulses
- Target penetration by the fuel cloud
- Fireball and hot temperature effects

In terms of fuel-air munition design they typically contain a central high-explosive burster charge which is surrounded by the fuel mixture. This could be a liquid, or fine powder or gas of some kind as described in the previous section. A smaller secondary igniter charge is also present, usually with some form of delay control. [13]

The process of munition function is as follows [15]:

1. Fuzing mechanism initiates burster charge
2. Casing of munition is broken apart and fuel is dispersed to form a cloud of gas/fine fuel particles
3. Delayed ignition charge initiates (timed delay to allow for appropriate cloud formation but ensuring initiation charge will be in close enough proximity to ignite fuel-air mixture)
4. Fuel-air mixture explodes forming fireball and shockwave.

Some important considerations when designing a fuel-air explosive are that case thickness should be minimised, this reduces the amount of work required by the burster charge to split the case and disperse the fuel – maximising cloud dispersion. The timed delay of the ignition charge is also critical as premature ignition of the fuel air mix may result in failure to ignite or lead to a reduction in explosive effects. Additionally the selection of fuel is important as a larger explosive limit range is preferable to fuels which will only explode in a narrow fuel-air ratio. [15] [16]

Comparison of fuel-air explosives to thermobaric weapons

Conventional fuel-air explosives and thermobaric weapons are both classed as a subset of volumetric explosives. This is because they do not act like a point-detonation as with conventional explosives due to the dispersion/detonation effects but rather as a detonation occurring throughout a volume of fuel. The main differences between a thermobaric weapon and a fuel-air explosive is that a thermobaric composition comprises of a high explosive and fuel-rich mixture. For example hydroxyl-terminated polybutadiene (HTPB) and a metal powder [17]. A thermobaric weapon differs in that it does not require a buster charge or a secondary ignition device. Instead, upon initiation of a thermobaric warhead the following sequence of events occurs:

- Anaerobic shock wave reaction of the high explosive travels through the material
- Fuel particles within the charge are dispersed and some react with the shockwave anaerobically
- Finally the dispersed fuel-rich mixture reacts aerobically with oxygen to combust [15]

The main advantages in using a thermobaric weapon over a fuel-air explosive is that they are less complex. They rely only upon reliable initiation at a desired distance from a target/upon impact to function and deliver their explosive and thermal effects to a target. In contrast, a fuel-air explosive device requires the ability to burst and disperse a fuel cloud in or around a target. Then this fuel cloud must be ignited by an ignition source, usually a secondary explosive device timed to allow for cloud formation from the fuel. This added complexity means more cost to design and develop true fuel-air explosive devices. Several thermobaric munitions have been developed around the world with the USSR (and later the Russian Federation) having developed several that have seen use in armed conflicts around the world. These include examples such as the RPO-A used in Afghanistan, to the munitions carried by the TOS 1A mobile artillery platform. [6] [6]

The distinction between fuel-air explosive devices and thermobaric explosives is often overlooked and the two terms are used interchangeably within open-source literature.

Suitable military targets for FAEs

When considering all of the properties of FAEs it is clear that they lend themselves to being deployed against certain targets.

Anti-structure capability – due to the large impulses that are achievable with fuel-air explosives, structures are an excellent target for FAE munitions. Larger impulses on the target structure mean it is under load for longer which increases the chances of severe structural damage compared to that achievable with a conventional explosive. The dispersion of a fuel-air cloud also means that they are less affected by terrain and structural protection. Clouds can spread across and into terrain features or structures which can aid in causing further damage. It is well known that confined explosions are a lot more damaging than open-air explosions due to the prevalence of reflected blast waves and concentration of explosive effects rather than dispersion and attenuation as seen in open-air. [18]

In a similar vein to structures, fuel-air explosives are excellent for clearing out cave systems due to the aforementioned reasons and the ability of the fuel-air mixture to permeate into cave systems.

Anti-mine capabilities – the large impulses that make fuel-air explosives excellent against structures also make them well-suited to clearing pressure-sensitive mines. Large fuel-air explosions can be

produced – the impulse of which will trigger pressure sensitive mines in a larger area. This is a safe and effective way at aggressively clearing large mine fields to support an advance. [16]

Vehicles – the large impulse damage also makes FAEs effective against light-skinned vehicles, grounded aircraft, and maritime targets. Grounded aircraft are specified due to the limited affects of a fuel-air explosive at the high operational altitudes of such vehicles. The susceptibility of ships to fuel-air explosions has been showcased by demonstrations such as the sinking of the USS McNulty [6]. To cause such damage to ships, the fuel air explosive must be deployed above the waterline as there is no atmospheric oxygen underwater. FAEs will have limited effect against hard armoured targets such as tanks. Although if a fuel-air cloud is allowed to penetrate through open hatches etc. then it could be devastating for any crew inside as well as promote cook-off of exposed ammunition due to exposure to high temperatures.

Vegetation clearance – FAEs have been used for landing site clearance due to the wide area of effect and intense fireball they produce being able to clear large swathes of land of vegetation. This makes them useful for preparing landing sites in densely forested environments for example. Examples of this include the deployment of FAEs by the USA during the Vietnam War. [5]

Anti-personnel – the effect on personnel from FAEs is profound, the large impulse and positive/negative phases can cause severe barotrauma to organs such as the lungs and membrane interfaces. In confined spaces where the effects of impulse are amplified these effects can be even more devastating. Although the primary cause of injury is due to blast wave damage the intense fireballs produced from FAEs can cause severe burns to targets, both external and internal if fuel has been inhaled. Additionally, if the fuel-air cloud fails to ignite, the inhalation of most fuels can still cause damage as some of the most common fuels are toxic to humans. [19]

A note on the ethical use of FAEs and thermobaric munitions:

Although fuel-air explosives and thermobaric weapons are not specifically banned from use by any conventions or treaties, their deliberate use in civilian populated areas could be considered a war crime under the Hague conventions of 1899 and 1907. Their use in the modern battlefield is frequently scrutinised by the media and attempts have been made to restrict their use in conflicts. This is primarily due to the extremely effective anti-personnel performance of such weapons against people in both open ground or in structures and fortifications. [6]

Conclusions

In conclusion, fuel air explosives are not a new phenomenon, but have been apparent for several hundred years. Although their devastating effects have been observed for such a long time period, munitions development to capitalise on this was not undertaken until the end of World War 2 at the earliest and has only been truly developed since the 1960s.

There are several factors to consider when seeking to understand FAE performance. These are the fuel type, saturation levels, particle sizes, atmosphere, environment, and initiation energy. All of which contribute to the performance of an FAE device.

The primary advantages from FAE as munitions is their ability to achieve far larger impulses than conventional explosives despite generating lower peak overpressures. Additionally fireball formation provides incendiary damage. These effects make FAE munitions particularly suited for use against targets such as lightly-armoured vehicles, structures, ships, and cave networks, whilst also being useful for mine clearance and landing zone preparation.

Although there is ample research and material on FAEs available in the open source domain – care should be taken due to their confusion with thermobaric weapons and the nuances and differences between the two not being well presented in the available literature and the media.

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FINAL GRADE

68/100

GENERAL COMMENTS

Instructor

Well done George. This assignment was well written, structured and referenced. Included many considered arguments. There were a couple of type-o, word omissions (see the second sentence on page 3) and sentence constructs that detracted from the overall presentation.

Comments in detail:

1. The history section is well researched and referenced.
2. You demonstrated a good understanding of the theory of FAE, and the factors affecting their performance. Just the right amount of explanation. However, you could have used a diagram to support your explanation of dispersion, delay and ignition.
3. 'Harness effect' not 'harness affect'.
4. I liked figure 1, which clearly demonstrates the difference between HE and FAE-type blast curves. You could have enhanced the figure by adding some potential values on the axes.
5. Good comparison is provided in Table 1.
6. The sequencing from theory to the practical application of FAE was well structured. Again, you

could have used a diagram to support your discussion on construction and function.

7. Burster not 'buster' charge. Severe, not 'sever'.

8. Types of target well explained across all environments (land/sea/air). FAE good for single impulse mines, but consider limitations for double/triple impulse etc.

9. Points on legality noted, but be careful as the LOAC all comes down to necessity, distinction and proportionality, unnecessary suffering etc - <https://lieber.westpoint.edu/are-thermobaric-weapons-lawful/>

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